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The Resource Allocation Effects of Environmental Policies

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Once, if you asked an economist what to do about externalities, the answer was sure to be: tax them. A number of questions have been raised about the traditional tax approach, and nontax approaches have continued to find more favor in actual policy. These developments help explain why interests of economists have widened to direct limitations on outputs and inputs, zoning, salable rights, legal recourse and a variety of other formal and informal arrangements (see Bohm, Buchanan, Ciriacy-Wantrup, Clarke, Dales, Kamien, Kneese, Mishan, Tideman, Tolley, Turvey, Upton, Wolozin, Wright, Zerbe).

The traditional economics literature on taxes and most of the recent literature on nontax policies have been qualitative. How to measure the benefits and costs of the policies has been neglected. The measurement task is often taken to be the obvious gathering of facts, not recognizing deficiencies in concepts needed for their collection and interpretation. Previous literature has tended to deal with one policy at a time. Different forms of control on polluting firms, procrusteanism of imposing uniform requirements, and spatial arrangements have been particularly neglected. A framework is needed for systematically comparing policies and indicating how effects depend on underlying demand and production conditions.

With these concerns in mind, the first section of this paper considers benefits from reducing a single negative externality. Results are obtained on how to use information on physical effects of the externality, on de-

NOTE: Helpful comments were made by Gardner Brown, Charles Upton, Richard Zerbe and University of Chicago urban economics workshop participants.

fensive acts of those harmed, and on factor rewards. Several needs for modifying benefit estimation practices emerge.

The second section considers the costs of reducing an externality through (a) emission regulation, (b) requirement of emission control equipment, (c) restrictions on inputs and (d) restriction on output. General cost expressions are developed, the policies are compared using algebraic forms, and applications of current interest are discussed.

After a third section on how to bring together benefits and costs with identical factors, the fourth section considers losses from identical requirements where there are uncertain multiple externalities with nonuniform factors. This section gives most attention to nonuniformity within a shed where physical effects are interrelated. Quantitative restrictions, taxes, salable rights and zoning—all of which are the same for a single externality under certainty—are compared. The final major section deals with location of activity between sheds giving attention to land bids needed for optimum location incentives.

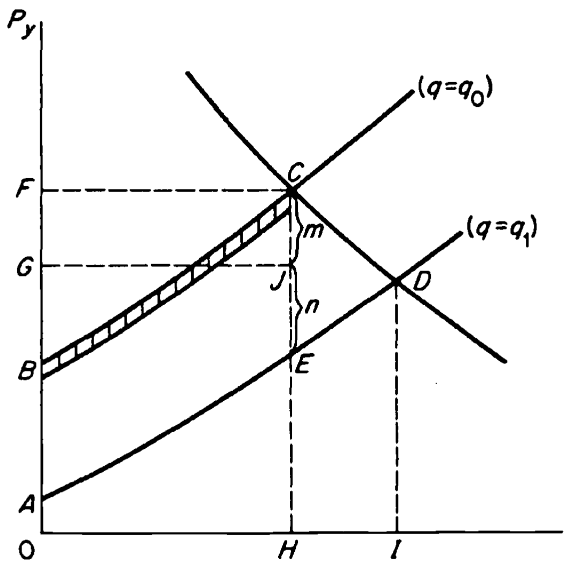
Damages and Defensive Acts

Firms

If reducing effluent will lower production costs of downstream firms, one part of benefits is the lowering in costs of producing the prevailing level of output downstream. Since the change in the total cost of producing the output is the sum of changes in marginal costs, this part of the benefit is equal to the sum of changes in the marginal cost of production from zero output up to the prevailing output downstream. If the demand curve facing the downstream firms is not completely inelastic, the lowering of marginal cost curves will increase the output at which marginal cost equals price. On each increment of increased output, there is a net gain equal to the difference between the demand value of the increment and marginal cost of production. The part of the benefit resulting from increased output of the downstream firms is the sum of the differences on each increment between the old and new output.

In Figure 1, *H* is output of the downstream firms prevailing before the reduction in the externality. The part of the benefits which is the change in cost of producing the prevailing output is the difference in marginal costs from zero up to *H*, or the area *ABCE*. As a result of reducing the externality, output expands to where the new marginal cost curve intersects the demand curve at output *I*. The part of the benefit due to additional output is the sum from *H* to *I* of incremental differ-

Figure 1



ences between demand value and marginal cost, or the area *CDE*. The total benefit from reducing the externality is the total of the areas *ABCE* and *CDE*, or *ABCD*. This is the standard result that benefit is equal to the change in producer plus consumer surplus [10].

Let the demand curve facing producers of a commodity y which is adversely affected by pollution be

$$p_y = F(y). \tag{1}$$

The production function is

$$y = y(z, q), \tag{2}$$

where z refers to inputs controlled by the producer. The variable q is a public good such as quality of water or air and is not controllable by the producer of y. The system is completed familiarly by equating marginal value of y to input price times inputs required to produce an extra unit of y:

$$p_y = p_z/y_z(z, q) \tag{3}$$

where $y_z(z, \hat{q})$ is the partial of (2) with respect to z and is the marginal product of z.

The right side of (3) is the marginal cost of producing y. Solving (2) for z and substituting into (3) gives marginal cost of producing y as a function of y itself, for different amounts of the public good q. Correspondence with the graph is established by noting that Figure 1 shows two of these marginal cost schedules and the demand curve (1).

Households

A first procedure possible for households would be to let environmental quality enter the utility function. A second procedure, to be followed here, is to exclude environmental quality from the utility function and let it be an input shifting the production for other goods which do enter the utility function. For instance, instead of entering the utility function, air quality is a production function shifter affecting goods which enter the utility function such as condition of buildings, clothing cleanliness, and freedom from respiratory and eye symptoms.

Under this second procedure the household problem is to maximize satisfaction from goods affected by environmental quality. Air quality affects inputs devoted to obtaining the goods. Among several advantages of this procedure, the analysis of benefits from improving environmental quality for the household becomes identical to that just given for the firm, permitting an institutionally neutral approach not arbitrarily affected by whether activity, such as laundering, takes place in the firm or household.

As applied to the household, Figure 1 shows how a lowering of environmental quality raises the marginal cost curve for attaining the goods on the x-axis which are affected by environmental quality. Defensive measures and other time and money responses to pollution are cost outlays devoted to the goods. The total cost outlay is the sum of the marginal costs up to the output achieved, or *OADI* at the higher level of environmental quality and *OBCH* at the lower level. The costs include housewife time in the case of cleanliness, and they include medical bills and time lost from work in the case of health. Even under adverse environmental conditions, medical bills and time lost from work are subject to choice since options would be not to have medical treatment and not to stay away from work, in which case health would be reduced below the low best level *OH* achievable with the reduced environmental quality.

To derive equations (1), (2) and (3) for the household, note that in contrast to the firm problem max $p_y y - p_z z + \mu_y[y - y(z, q)]$, the problem for the household is max $U(y, z') + \mu_y [y - y(z, q)] + \mu_z(Z - p_z z - p_z' z')$ where Z is total wealth and z' is all other goods. For the firm, given the demand curve (1) and the production function (2), the derivation of (3) by Lagrangian maximization is straightforward. For the household, the production function (2) is given, but no price of y or demand curve are given. Letting p_y be the internal demand price or amount of money the household is willing to give up to get an extra unit of y, this amount of money must be such that the utility from spending an extra dollar on y and z' are the same, $U_y/p_y = U_{z'}/p_{z'}$ (see Becker), or rearranging $p_y = (U_y/U_{z'})p_{z'}$. Using the budget constraint to substitute out z' and taking $p_{z'}$ as given, the foregoing price condition gives the internal demand curve (p_y as a function of y) which is equation (1) for the household. Using the price condition together with the Lagrangian solution to the household maximization problem gives $p_y = p_z/y_z$ which states that marginal valuation is equated to marginal cost of producing y and is equation (3), completing the demonstration that the same system is obtained for the firm and household.[1]

The expenditure approach

The effects of air quality on household expenditures are often estimated to gain an idea of the benefits of air pollution reduction (see Ridker).

1. The Lagrangian solution to the household maximization problem in the text can be written $U_z = U_y y_z$. Indicating the variables appearing in each function and using the production function $y = y\ (z, q)$ to eliminate y, the equilibrium condition for the text formulation—where environmental quality does not enter the utility function—is $U_{z'}(z', z, q) = U_y(z', z, q)y_z(z, q)$.

If environmental quality does enter the utility function, expenditures on things z affected by environmental quality are considered to be expenditures on goods with utility, instead of being expenditures on inputs. The formulation of the household maximization problem becomes max $U(z', z, q) + \mu_z(Z - p_z z - p_z z')$ for which the equilibrium condition is $U_{z'}(z', z, q) = U_z(z', z, q)$.

Compare the right sides of the equilibrium conditions under the two different formulations. If environmental quality enters the utility function as in the formulation just given in this footnote, the marginal utility of things affected by environmental utility is seen, in terms of the text formulation, to be a product whose unobserved components are the marginal utility of the output affected by environmental quality times the marginal productivity of inputs in producing the output.

If environmental quality enters the utility function, activities which are responses to pollution must enter as related goods. They have to be analyzed in terms of "substitutability" with environmental quality, which seems arbitrary and prevents consideration of the more ultimate household satisfactions y. Because of the suppression of ultimate satisfactions, information on health and other physical measures of well-being cannot be used in benefit estimation using the formulation, given in this footnote, where environmental quality enters the utility function.

The change in expenditures is the difference between *OADI* and *OBCH*. Since the two costs have *OAEH* in common, the change in expenditure is *ABCE* minus *HEDI*. *ABCE* is the change in costs necessary to maintain the level of y at H, and is equal to $ky\Delta C$ where ΔC is the vertical shift in marginal cost at H and k is the ratio of the average of vertical shifts at all the previous values of y relative to the shift at H. Expressed as a percentage of the value of $p_y y$, $ABCE/p_y y$ is $k\Delta C/C$ since at the margin price p_y equals marginal cost C. The area *HEDI* is $p_y \Delta y$ minus the area *EJD*, which in turn is $n\Delta y/2$. Making use of the fact that the elasticity δ of the marginal cost curve is $(\Delta y/n)(C/y)$ and again expressing results as a per cent of $p_y y$, $HEDI/p_y y$ equals $(\Delta y/y)[1 - (\Delta y/y)/2\delta]$. To find $\Delta y/y$, making use of the fact that the elasticity of demand β is $(-\Delta y/m)\ (p_y/y)$ and of the expression for δ, obtain $m + n = \Delta C$ as a function of Δy. Solving for Δy and dividing by y gives $(\Delta y/y) = (\Delta C/C)$ $\{1/[(1/\delta) - (1/\beta)]\}$. These results may be combined to obtain changes in expenditures as a percentage of value

$$\Delta E/p_y y = (\Delta C/C)\{k + \beta[1 + \beta(\Delta C/C)/2(\delta - \beta)]/[1 - (\beta/\delta)]\}. \quad (4)$$

The special case of a horizontal marginal cost curve is

$$\Delta E/p_y y = (\Delta C/C)(1 + \beta) \quad \text{if} \quad \delta = \infty \quad \text{and} \quad k = 1. \quad (4\bar{C})$$

Extra effort over a wide range should continue to yield substantial effects on physical characteristics defining cleanliness, thus suggesting that marginal cost is fairly constant for attaining these attributes and thereby proving ($4\bar{C}$) a good approximation for cleanliness. A commonly reported finding is that higher pollution does not lead housewives to devote more effort to cleaning. Contrary to the inference one might be tempted to draw that there are no cleanliness benefits, a possibility is that the elasticity of demand for cleanliness is unity ($\beta = -1$) since this is the only condition making the right side of ($4\bar{C}$) zero. Even with error in answers, the lack of perceptible expenditure response under extreme pollution conditions suggests a downward response of cleanliness demanded to a rise in its cost ($\beta < 0$).

The area *ABCE* is $-k\Delta C/C$ as already noted. The additional benefit area *CDE* is $(\Delta y)(\Delta p)/2 - (\Delta y)(\Delta C - \Delta p)/2$ or $-(\Delta y)(\Delta C/2)$. Adding the two areas, making use of the solution for $\Delta y/y$ and dividing by $p_y y$ gives benefits as a fraction of product value:

$$\Delta B(y)/p_y y = -(\Delta C/C)\{k + (\Delta C/C)/2[(1/\delta) - (1/\beta)]\}, \quad (5)$$

which reduces to

$$\Delta B(y)/p_u y = -(\Delta C/C)[1 - \beta(\Delta C/C)/2] \quad \text{if} \quad \delta = \infty \quad \text{and} \quad k = 1. \qquad (5\bar{C})$$

Cleanliness

Comparing ($4\bar{C}$) and ($5\bar{C}$) makes clear that zero change in expenditure ($\beta = -1$) does not indicate that benefits are zero. Under conditions that seem typically satisfied of rises in marginal costs less than one hundred per cent and absolute value of elasticity of demand of one or less, benefits in ($5\bar{C}$) are the same order of magnitude as the use in marginal cost.

Suppose marginal cost of maintaining household cleanliness is raised twenty-five per cent due to heavy pollution in a neighborhood. Assuming $\beta = -1$, $\delta = \infty$, and $k = 1$, ($4\bar{C}$) indicates change in expenditures is zero while ($5\bar{C}$) indicates costs (negative benefits) are 28.1 per cent of the total expenditures for cleanliness. If the yearly value of materials and time expended on cleanliness is $1,000 per household, the pollution costs are $281 per household of $2.81 million per year for a neighborhood of 10,000 households showing that pollution costs may be substantial even in the absence of an observed expenditure response.

Medical services

Instead of being horizontal, marginal cost curves may be upward sloping and may be shifted nonuniformly. For a disease, the abscissa is an index of freedom from the disease symptoms. In the absence of pollution, rising marginal costs might be encountered only at a health level far to the right. With air pollution, the marginal cost curve would be shifted up and could become more steeply sloped at a lower level of health. For a disease with high treatment costs or debilitating effects, the relative rise in marginal cost $\Delta C/C$ may be high at H, and change in marginal cost at H may be greater than average change in marginal cost on the units of x to the left of H. At the lower level of cost, which Figure 1 indicates to be the relevant cost curve for the calculation, the supply curve might be highly elastic. The fact that expenditures are observed to increase is suggestive that the demand elasticity is less than one. If $\Delta C/C = .10$, $k = 2$, $\delta = 7.5$ and $\beta = -.5$, (4) and (5) give $\Delta E/p_u y = .153$ and $-\Delta B/p_u y = .205$.

At the extreme, if no defensive expenditures are possible, the marginal cost curves become vertical lines. With no observed changes in expenditures, the benefits are determined entirely by the slope of the demand curve ignored in the expenditure approach.

Mortality

The model of (1) – (3) can guide studies of physical effects of pollution. The benefit of a one-unit change in environmental quality is the sum of the effects on marginal costs of all units of x up to the observed level, illustrated as the sum of the small quadrangles in Figure 1. In view of (3), the sum is $\int_0^y [d(p_z/y_z)/dq]dY$. Carrying out the differentiation under the integral sign, substituting in $p_y = p_z/y_z$ and making use of $dY = y_z dZ$ to change the variable of integration gives as the sum of quadrangles $\int_0^z p_y y_{zq} dZ$ which equals $p_y y_q$ and says that the benefit from a one-unit change in environmental quality is the value of a unit of y times the effect of the environmental change on y. Another way of representing the benefit area $ABCE$ plus CDE thus is

$$B(y) = \int_{q_0}^{q_1} p_y y_q \, dQ, \qquad (6)$$

which suggests how measures of pollution effects y_q on physical attributes should enter benefit estimation. Note that y_q is a marginal productivity concept holding all other inputs z constant.

Suppose the only health effects of air pollution are small effects on probability of survival, which probability is the good measured as the abscissa. Suppose the change in probability is so small that the marginal value of survival is not affected (demand curve flat over the range being considered) and there are no defensive measures (marginal cost curves perfectly vertical). Then equation (6) indicates the appropriate measure of benefits is the observed change in survival expectancy times p_y, a measure of the value of life.

Morbidity

If the demand curve is not flat or if defensive expenditures are undertaken, as is the rule for morbidity, in applying (6) one must first allow for changes in marginal value p_y along the demand curve. Econometric studies are conceivable estimating sacrifices people are willing to make to avoid physical effects as a way of facing this valuation problem. Second, the effect of the expenditures on physical attributes needs to be subtracted out to obtain the sole effect y_q of pollution or physical attributes. The observed association between morbidity and pollution understates the benefits from pollution reduction since morbidity is reduced by defensive expenditures. Clinical data might throw light on effects of defensive measures and might also be used to directly estimate y_q if situations can be found of the same defensive measure under different pollution levels. For damages to materials, as opposed to human beings, controlled observations are promising.

Land and labor returns

The problems of goods definition encountered in analyses of expenditures and physical effects do not arise in the factor rewards approach. Since any environmental effect which is less than nationwide can be escaped by moving, given consumer knowledge the shaded benefit area *ABCE* plus *CDE* can be expected to show up as a factor reward difference, estimable without the conceptual problems surrounding Figure 1. The idea that air quality differences within a city are reflected in land values, provides a rationale for benefit estimates based on econometric studies of pollution effects on residence values (see, for example, Crocker and Anderson).

Environmental effects pervading an entire city are not mutable by a residence change within the city. However, because they are mutable by moving between cities, they can be expected to show up in differences in wages between cities. In contrast to work on land values, there has been little estimation of environmental effects on wages. To indicate possibilities, a preliminary result by Oded Izraeli is a regression of deflated wages of laborers in SMSAs on human capital, public expenditure and environmental variables. The R^2 is .81. Regarding air pollution, the elasticity of wages with respect to sulfates is .09 and with respect to particulates is .01. Both signs are as expected, and the coefficient of sulfates is significant above the 5 per cent level.

Productivity of Pollution

Turning from benefits to costs, the costs of pollution reduction consist of losses in satisfaction from commodities whose production causes pollution. In the absence of incentives to control pollution, pollution can be ignored as a consideration in production of these commodities. The traditional theory of production without controls suffices. If pollution is reduced from the point of no control, losses may be incurred because less of the product is produced and it is produced in a higher cost way. While the existence of pollution control costs has been recognized, the reasons for losses have not often been considered explicitly. At most, even in theory, a cost schedule for reducing emissions is usually assumed as a starting point without being derived.

To find out why and by how much the costs of different methods of control differ, in addition to needing to know about product demand and the traditional production function for product output, knowledge is needed about an additional production function indicating how pollutant emissions depend on producer decisions. Specifically, emissions depend on waste producing inputs and pollution control inputs. In this section, it will be shown that the production function for emissions is a key determinant of differences in policy costs. Under an emission regulation policy, producers can choose between adjusting waste producing inputs and pollution control inputs. Because they can choose, this policy is least costly. Under requirement of pollution control devices, producers have incentives to reduce emissions using the devices but not to adjust waste producing inputs; whereas under regulation of waste producing inputs, these incentives are reversed. The relative costs of the latter two policies depend on the marginal effects on emissions of pollution control devices and waste producing inputs. The most costly policy of all is restriction of product output, under which the only reason for emission reduction is a fall in output, with no action being taken to reduce emissions caused by any given output.

Policy effects can be analyzed as responses to incremental exogenous changes. The marginal emission benefit is achieved by allowing emissions to increase one unit through incremental changes in a policy, as for example, the benefit from relaxing restriction on waste producing inputs just sufficiently to allow emissions to increase by one unit. The cost of a policy (measured as benefit foregone) is the sum of marginal benefits from allowing emissions to increase from their level under the policy up to the uncontrolled level. Since uncontrolled emissions are pushed to the point where they have no further value, marginal benefit is zero from allowing emissions to increase at the no control equilibrium under any policy. The magnitude of total benefits foregone depends on how rapidly marginal benefits decline in approaching the no control equilibrium. Thus comparing policies requires comparing *change in marginal benefits* as emissions are allowed to increase. After presenting the no control model, a model of producer decision will be set up for each policy, from which will be derived marginal benefits, change in marginal benefits and the resulting policy costs.

No control

Let the demand curve for a commodity whose production causes pollution be

$$p_x = D_x(x) \tag{7}$$

where p_x is price or value of an extra unit of x. For a producer having no effect on price, p_x is given implying the slope D_{xx} is zero. If output affects price, as for a local utility, it will be assumed that regulation enforces marginal cost pricing, leaving for future analysis other pricing policies. If the polluting entity is a household, the price is marginal valuation within the household. The incentive is then to maximize the area under the curve less foregone expenditures in producing the commodity.

In the absence of expenditures to reduce emissions, the only physical relation of concern to the producer is the traditional production function explaining product output:

$$x = x(u, f), \tag{8}$$

where f consists of inputs such as coal or gasoline which are polluting and u consists of all other inputs that increase the production of x. The assumed demand conditions imply familiar incentives to make output price times marginal physical product equal to input price. The problem is max $\int_0^x D(X)dX - p_f f - p_u u + \lambda_x[x - x(u, f)]$, whose solution by Lagrangian maximization gives:

$$p_x x_u = p_u, \tag{9}$$

$$p_x x_f = p_f, \tag{10}$$

where x_u and x_f are the partials of (8) and p_u and p_f are the input prices.

Equations (7)–(10) determine commodity price, output, and the two inputs in the absence of efforts to control pollution. They describe market behavior toward pollution assuming there are free rider and other impediments to private negotiations. To consider how changes will affect this system, a generalized displacement can be represented by taking the differential of each equation. The resulting coefficients of differential changes are:

$$\begin{array}{cccc} dx & dp & du & df \end{array} \qquad dE$$

$$\begin{bmatrix} D_{xx} & -1 & 0 & 0 \\ -1 & 0 & x_u & x_f \\ 0 & x_u & px_{uu} & px_{uf} \\ 0 & x_f & px_{fu} & px_{ff} \end{bmatrix} = \begin{bmatrix} e_x \\ e_p \\ e_u \\ e_f \end{bmatrix}. \qquad \begin{matrix} (7') \\ (8') \\ (9') \\ (10') \end{matrix}$$

The determinant on the left hand side will be denoted M. On the right hand side dE refers to any exogenous change. The coefficients e_x, e_p, e_u and e_f indicate the effect, if any, of the change in each equation. With no controls, exogenous changes refer to shifts in demand function, production function or factor prices. With controls, the exogenous changes can also refer to incremental changes in a policy control.

Emission regulation

The production function specifying emissions is:

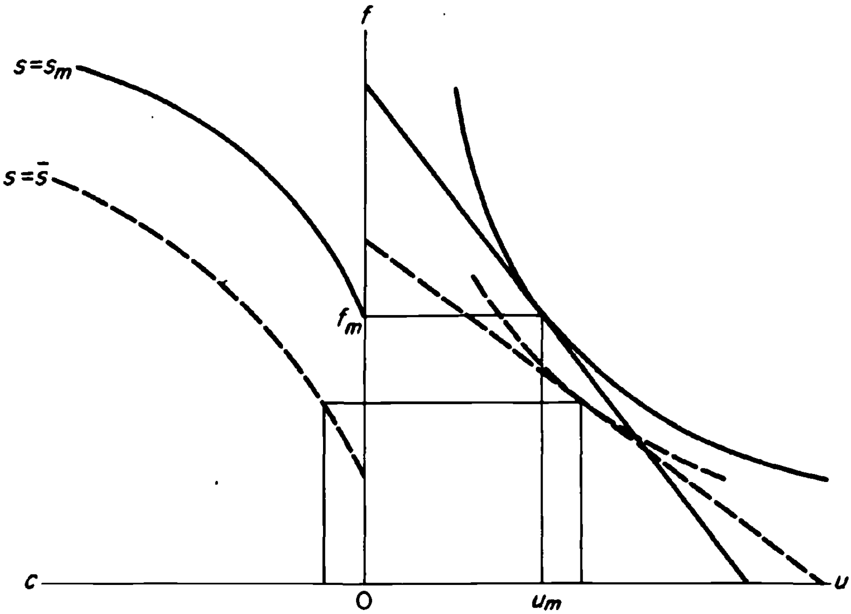
$$s = s(f, c) \qquad (11)$$

where c refers to inputs devoted to controlling emissions. The polluting inputs f increase emissions, and control inputs c decrease them.

One set of policies of interest theoretically and practically operates on emissions s; e.g., s is limited to some maximum amount. This type of policy induces producers to use less polluting inputs and to incur emissions control expenditures. With a given limit of allowable emissions, the marginal cost to the producer of adding a unit of polluting input is the input price *plus* the cost of controlling the emissions from the extra input. The extra emissions are given by the partial of the emission relation (5) with respect to f, or s_f. For example s_f is pounds of smoke resulting from an extra ton of coal. Since adding one unit of precipitator inputs will reduce pounds of smoke emitted by $-s_c$, precipitator inputs required per pound of smoke reduction are $-1/s_c$. Multiplying the precipitator inputs required per pound of smoke by the extra pounds of smoke gives $-s_f/s_c$, the control inputs required to keep emissions from increasing. The magnitude $-s_f/s_c$ is the marginal rate of substitution between control inputs and polluting inputs and will be denoted σ. The cost of controlling emissions from an extra unit of polluting inputs is this amount times the price of control inputs or $p_c\sigma$. In contrast to (10), the conditions governing use of polluting inputs becomes

$$p_x x_f = p_f + p_c\sigma. \qquad (10s)$$

Figure 2



The control costs $p_c\sigma$ add to the marginal cost of using polluting inputs, giving incentives to use less of them.

Equations (7)–(9), (10s) and (11) describe the system under the regulation controlling s. As compared with the free market system, there is an additional endogenous variable c. In the free market system, there are no incentives to use control inputs ($c = 0$). If the regulation is effective, c will take on a positive value.

Free market and the control situation are compared in Figure 2. The right side contains iso-product curves for x. The free market inputs f_m and u_m are determined in the usual manner by tangency between an iso-product curve and factor cost line having slope $-p_u/p_f$. With an emission standard, the slope of the factor cost line is the dashed line $-p_u/p_f + \sigma p_c$. The left side of Figure 2 contains iso-emission curves. Taking the differential of (11) holding s constant and solving for df/dc gives slope of iso-emission curve $-s_c/s_f$, the reciprocal of σ. If allowed emissions are lowered from the free market level s_m to $\bar{s}$, the producer contemplates positions along the new iso-emission curve, each position implying a different slope of marginal factor cost line on the right side. For any choice of c on the left side, an optimum production decision for x on the right side can be found. Suppose the producer was temporarily at some non-equilibrium point on the iso-emission curve. This would determine σ and hence the slope of the marginal factor cost line whereupon, dividing (10s) by (9) an expansion path for x and u could be found. The producer would proceed along the expansion path until marginal cost equalled marginal gain. Having found this position, he could ask whether further gains could be made by changing emission control expenditures c thus changing allowable fuel use. Since σ units of c are required to increase fuel use by one unit while still being able to meet the emission standard, the emission control cost required to expand fuel use by one unit is $p_c\sigma$. The gain from the expansion of fuel use is the marginal revenue from additional fuel use less the resource cost of the fuel or $p_x x_f - p_f$. The producer will be in full equilibrium in the use of fuel only when he has moved out the iso-emission curve to where (10s) is satisfied. Fuel use and control expenditures are thus simultaneously determined by the factor use condition (10s) and the requirement not to exceed allowable emissions (11).

To find effect of changing allowable emissions, take the differentials (7) – (9), (10s) and (11). If adjustments are too small to affect variable input prices, the only exogenous change will be the change $d\bar{s}$ in allowable emissions. The solutions for induced changes in fuel use and control expenditures are

$$df/d\bar{s} = p_c\sigma_c M_{ff}/M_s, \tag{12s}$$

$$dc/d\bar{s} = (M - p_c\sigma_f M_{ff})/M_s, \tag{13s}$$

where $M_s = s_c M + (s_f\sigma_c - s_c\sigma_f)p_c M_{ff}$. The first subscript of a double subscript for M indicates the deletion of a row, and the second indicates deletion of a column.

The benefits from producing x are $b(x) = \int_0^x D(X)dX - p_u u - p_f f - p_c c$, that is, the consumption benefits less the input costs. The change in benefits from imposing an incremental adjustment in s is obtained by differentiating benefits with respect to s to obtain $b(x)_s^{\bar{s}} = p_x(dx/ds) - p_u(du/ds) - p_f(df/ds) - p_c(dc/ds)$. This expression can be simplified by inserting the derivative of the production function for commodity output (8) with respect to s, $(dx/ds) = x_u(du/ds) + x_f(df/ds)$, into the change in benefits to eliminate (dx/ds), giving $(p_x x_u - p_u)(du/ds) + (p_x x_f - px_f - p_f)(df/ds) - p_c(dc/ds)$. Substituting in the marginal productivity conditions (9) and (10s) further simplifies the change in benefits to $b(x)_s^{\bar{s}} = p_c\sigma(df/d\bar{s}) - p_c(dc/d\bar{s})$. The first term on the right side is the excess $p_c\sigma$ of the marginal benefits from fuel use over the marginal resource cost of fuel, times the change in fuel resulting from a one-unit change in allowed emissions $\bar{s}$. The second term is the resource cost of emission controls c resulting from a unit change in s. The simplifications leading to $b(x)_s^{\bar{s}}$ make use of the idea that in a no control equilibrium the total benefits in the production of x are maximized implying marginal benefits are zero; i.e., extra resources devoted to x are just worth the benefits obtained. A change in benefits when s is changed occurs only if the marginal conditions are not fulfilled. The change in benefits is the difference between the marginal resource costs incurred for those inputs not being used so as to maximize benefits in the production of x.

The change in benefits can be simplified further because the two terms in the centered expression for $b(x)_s^{\bar{s}}$ just given are control cost effects. The term $-p_c(dc/d\bar{s})$ is the direct change in control costs as a result of a change in allowable emissions and would be the entire change in benefits if there were no induced change in f. On the other hand, if there were no change in control costs and the entire adjustment was to change f, adjustments in control costs would be avoided. A reduction in fuel use of one unit reduces emissions by s_f making it possible to avoid reducing control inputs by s_f/s_c. Since $\sigma = -s_f/s_c$ the saving on control costs is $p_c\sigma$. Differentiation of the emission relation (11) with respect to $\bar{s}$ gives as a necessary condition between fuel and control input changes $1 = s_c(dc/d\bar{s}) + s_f(df/d\bar{s})$ indicating that the sum of the emissions changes due to control input and fuel adjustment must equal the total emissions change. Rearranging, the change in fuel is $df/d\bar{s} = [1 - s_c(dc/d\bar{s})]/s_f$ or the part of the emission change not met through control costs divided by change in emissions per unit of fuel change. Substituting this change in fuel into the expression for $b(x)_s^{\bar{s}}$ gives

$$b(x)_s^{\bar{s}} = -p_c/s_c. \tag{14s}$$

The benefit resulting from a change in allowed emissions reduces the control cost saving that would be made possible by allowing a one-unit emissions change, holding fuel constant. Comparing with the previous expression for $b(x)_s^{\bar{s}}$ the benefit is not the actual control cost change but rather is what the control cost change would be if the entire adjustment in emissions were achieved via a change in control inputs.

The slope $b(x)_{ss}^{\bar{s}}$ of the marginal benefit schedule, needed to evaluate the cost of an emission regulation, can be found by differentiating (14s) with respect to s to obtain

$$b(x)_{ss}^{\bar{s}} = (p_c/s_c^2)[s_{cf}(df/d\bar{s}) + s_{cc}(dc/d\bar{s})] \tag{15s}$$

where $df/d\bar{s}$ and $dc/d\bar{s}$ are given by (12s) and (13s).

Pollution control devices

A second type of policy would not control emissions directly but would require producers to undertake emission control expenditures, making $\bar{c}$ exogenous. There are then no incentives to hold down fuel use. The producer model consists of (7) – (10) plus the condition that c is exogenous, which is the same as the free market model except that c is nonzero. The cost of this policy is simply the emission control expenditure. The effect on benefits (negative of costs) of a one-unit change in emissions achieved through altering control inputs is input price p_c times the $1/s_c$ emission control inputs required to reduce emissions by one unit.

$$b(x)_s^{\bar{c}} = -p_c/s_c. \tag{14c}$$

The right hand sides of (14s) and (14c) are identical because benefit change (14s) under the $\bar{s}$ policy can be expressed as a hypothetical control cost expenditure that would be necessary. In (14c) the change in expenditure is actual.

The *change in marginal benefits* with respect to *emission control inputs* is the derivative of (14c) with respect to c, or $-p_c s_{cc}/s_c^2$. The slope being sought is the change in marginal benefits with respect to *emissions* and is this derivative divided by the associated change in emissions $ds/d\bar{c}$. Since there are no incentives to change f, $ds/d\bar{c}$ is obtained by differentiating (11) with respect to c holding f constant or s_c. Thus the slope of the marginal benefit schedule under the policy of controlling c is

$$b(x)_{ss}^{\bar{c}} = p_c s_{cc}/s_c^3. \tag{15c}$$

Restricting waste producing inputs

The simplest example of a policy operating through waste producing inputs is a direct control on an amount of a fuel. Instead of choosing fuel according to (4) or (4s), fuel f becomes exogenous. The producer model then is (7) – (9) determining price of output p_x, output x and nonfuel inputs u. Since no incentive is given to make emission control expenditures, $c = 0$.

Differentiate benefits $\int_0^x D(X)dX - p_u u - p_f f - p_c c$ with respect to f, substitute in the derivative of the production function with respect to f, and make use of (9) and the condition that $c = 0$ to ascertain that the change in benefits with respect to f is $p_x s_f - p_f$, or the difference between marginal revenue and marginal cost from the extra unit of f, which is reasonable since the other inputs are either in equilibrium or are zero. Since the amount of fuel needed to reduce emissions by one unit is $1/s_f$, the effect on benefits of a unit change in emissions achieved through reducing fuel inputs is

$$b(x)_s^{\bar{f}} = (p_x x_f - p_f)/s_f. \tag{14f}$$

It was possible to express benefit change under general emission control (14s) in terms of control costs because the difference between marginal revenue and marginal cost of fuel $p_x x_f - p_f$ was equal to addition to control costs required due to adding fuel, i.e., from (10s) $p_x s_f - p_f = p_c \sigma$. The latter equality does not hold under the fuel restriction policy. As f is reduced, the divergence between marginal revenue and marginal cost will grow. The value of $\sigma = -[s_f(f, 0)]/[s_c(f, 0)]$, or the control inputs that would be required to keep emissions from increasing when f is changed, might be altered little if at all. Thus (14f) must remain as stated with no conversion to equivalent control cost.

To obtain the *change in marginal benefits* with respect to *fuel*, differentiate (14f) with respect to f to obtain $[p_x x_{fu}(du/d\bar{f}) + p_x x_{ff} + x_f(dp_x/d\bar{f})]/s_f$. This approximation holds as long as the second term in the differentiation is zero $\{-[(p_x x_f - p_f)/s_f^2]s_{ff} = 0\}$, which is necessarily so at the free market equilibrium where $p_x x_f - p_f = 0$. The approximation remains good as long as the fuel restriction is not so severe as to raise $p_x x_f - p_f$ to a significantly large value. Another defense of the approximation is the likelihood that s_{ff} will be small. The reasonable assumption that, with zero emission controls, emission will tend to be proportional to fuel input, implies s_{ff} is zero, making the term in question drop out. This assumption is used in the functional form examples later.

Take the differentials of (7) – (10) letting f change exogenously, and solve the linear system to obtain $du/d\bar{f} = -M_{fu}/M_{ff}$ and $dp_x/d\bar{f} = M_{fp}/M_{ff}$. Substitute these results into the change in marginal benefits resulting from a change in fuel given at the beginning of the previous paragraph, factor out $1/M_{ff}$ from the bracket, and note that the bracket then equals M. The change in marginal benefits from a unit change in *emissions,* achieved via an input policy such as fuel restriction, is obtained by dividing $ds/d\bar{f}$ $(= s_f)$:

$$b(x)_{ss}^{\bar{f}} = (1/s_f^2)(M/M_{ff}). \qquad (15f)$$

A policy giving the producer equivalent incentives to adjust the amount of fuel would be a tax on fuel equal to $p_x x_f - p_f$, i.e., a tax making an equivalent divergence between marginal revenue and marginal resource cost of coal. From (14f) it is seen that the marginal benefits are proportional to the amount of this tax. The *change* in marginal benefits is then proportional to the change that would occur in such a tax. M/M_{ff} on the right side of $b(x)_{ss}^{\bar{f}}$ is the reciprocal of the response of fuel use to a change in fuel price and is thus, in fact, equal to the change in tax that would be necessary to bring about a unit change in fuel use, which is then converted to an emissions basis by the $(1/s_f^2)$ term.

Restricting output

A fourth type of policy seeks to control emissions even more indirectly, through affecting the producer's decision as to amount of x produced. The simplest example is a direct restriction making x exogenous. In the model of producer decision, the demand relation (7) is dropped since the regulation of x prevents the producer from adjusting output to demand. The model then consists of the production function (8) and the factor demand relations (9) and (10) in which price of output p is replaced by the marginal cost of output λ. The producer adjusts factors to minimize the cost of a given output but is unable to carry output to where $p = \lambda$. In the other models, where x is not controlled, marginal cost equals price making it unnecessary to distinguish between p and λ.

Since the derivative of benefits with respect to x is $p_x - p_u(du/dx) - p_f(df/dx)$, since (3) and (4) permit the substitutions $p_u = \lambda x_u$ and $p_f = \lambda x_f$, and since the derivative of the production function (2) with respect to x gives the substitution $1 = x_u(du/ds) + x_f(df/ds)$, the marginal benefit from a change in x reduces to $p_x - \lambda$ which, reasonably, is the value of an extra unit of x minus the cost of producing it. The *marginal benefit* with respect to *emissions,* achieved through the exogenous changes in x, is obtained as in the other cases by dividing by the change in emissions resulting from the change in x:

$$b(x)_s^{\bar{x}} = (p_x - \lambda)/s_f(df/dx). \qquad (14x)$$

Using the same logic as for the fuel restriction policy, the *change in marginal benefits* with respect to *emissions* when x is changed, $b(x)_{ss}^{\bar{x}}$, is $(1/s_f^2)[(dp_x/dx) - (d\lambda/dx)]$ divided by $(M_{xf}/M_{xx})^2$ which is the square of the fuel change resulting from a change in x obtained from solving (8′) – (10′) with x exogenous. Also from (8′) – (10′), $d\lambda/dx = -M_{xp}/M_{xx}$. From the demand relation (1), $dp_x/dx = D_{xx}$. Making these substitutions in the expression for $b(x)_{ss}^{\bar{x}}$, factoring out $1/M_{xx}$ from the bracket and noting that the bracket then equals M, gives as the slope of the marginal benefit schedule for the case where output is controlled

$$b(x)_{ss}^{\bar{x}} = (1/s_f^2)(M_{xx}/M_{xf})(M/M_{xf}), \tag{15x}$$

which can be interpreted as the change in tax on output required to change emissions by a unit $M/M_{xf}s_f$, divided by the change in emissions per unit change in output s_fM_{xf}/M_{xx}.

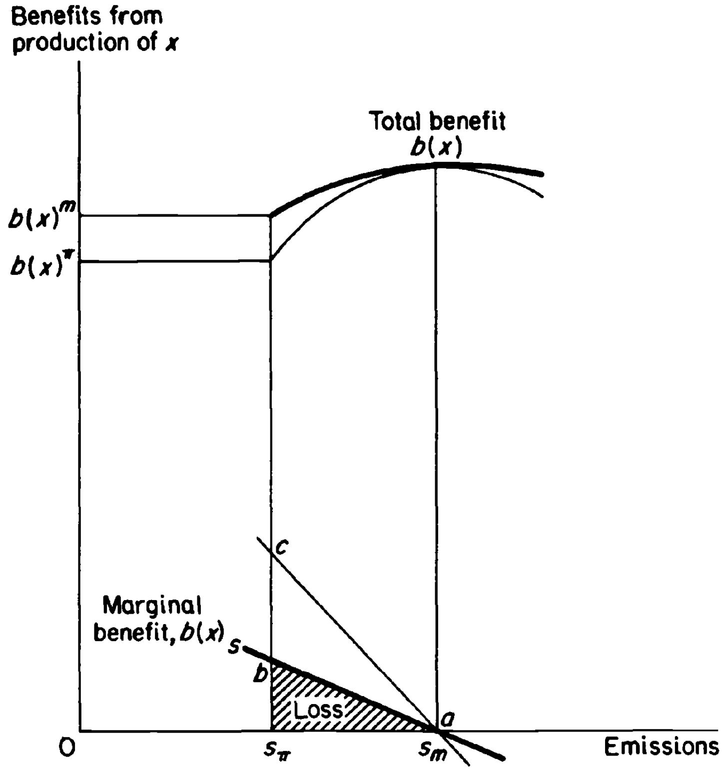
Comparison of the four policies

The curved lines in figure 3 are total benefits from x and are a maximum $b(x)^m$ at the free market level of emissions s_m. Benefits from x are reduced as one moves to lower emissions. The dark curved line shows the benefits from x under one particular policy. The dark straight line is the marginal benefit curve from x for this policy. The light lines in Figure 3 pertain to an alternative policy. The cost of a policy is the difference between free market benefits and benefits under the policy, or $b(x)^m - b(x)^\pi$ where π denotes the policy. This cost is the shaded area under the marginal benefit schedule in figure 3.

The cost is the sum of marginal benefits in going from free market emissions s_m to emissions s_π under the policy, or $[b(x)^m - b(x)^\pi] = -[\int_{s_\pi}^{s_m} b(x)_s^\pi ds]$ $b(x)_s^\pi ds$. Marginal benefit at the free market solution is marginal benefit at any lower level of emissions s plus the sum of changes in marginal benefits going from the lower level up to the free market level, or solving for the marginal benefits at the lower level $b(x)_s^\pi = b(x)_s^m - \int_s^{s_m} b(x)_{ss}^\pi\, dS$. Substituting this result into the expression for cost and assuming free market marginal benefits from pollution are zero, the cost of any policy π is:

$$b(x)^m - b(x)^\pi = \int_{s_\pi}^{s_m} \left[\int_s^{s_m} b(x)_{ss}^\pi\, dS\right] ds. \tag{16}$$

Figure 3



If the marginal benefit schedule can be approximated as linear, $b(x)_{ss}{}^{\pi}$ is constant giving as the cost of any policy π:

$$b(x)^{m} - b(x)^{\pi} = b(x)_{ss}{}^{\pi}(s_m - s_\pi)^2/2, \tag{16L}$$

verifiable as the shaded area by inspection. For a given emission reduction, the costs of the policies are thus proportional to the slopes $b(x)_{ss}{}^{\pi}$ of the marginal benefits schedules (15s), (15c), (15f) and (15x).

A possible functional form for the emission relation (11) is $s = mfe^{-kp_c c/p_f f}$, where m is emissions per pound of fuel if there are no control inputs and k is the percentage reduction in emissions per pound of fuel resulting from an extra dollar of expenditures on control inputs relative to fuel. Evaluating (15s) with this functional form, inserting the result into (16L) and dividing by $p_f f$ reveals that the estimated cost, relative to fuel expenditures, of a policy of regulating emissions is

$$[1/(-k + \eta_f)](a^2/2), \tag{16s}$$

where a is the reduction in emissions as a per cent of total emissions and η_f is the own price elasticity of demand for fuel. Similarly, the cost relative to fuel expenditures of a policy of requiring emission control inputs is

$$(1/-k)(a^2/2). \tag{16c}$$

The cost relative to fuel expenditures of restricting fuel inputs is

$$(1/\eta_f)(a^2/2). \tag{16f}$$

Finally, the cost relative to fuel expenditures of restricting the firm's output is

$$(1/-v\eta_x)(a^2/2), \tag{16x}$$

where v is the change in value of fuel inputs per unit of output accompanying a change in output and η_x is the elasticity of demand for fuel with respect to the price of output.

With regard to the last policy, the elasticity η_x in (16x) is a firm scale effect. The only reason that fuel use is affected by the price of x is that there is a product output response which changes all inputs. On the other hand, the elasticity η_f in (16f) contains both a scale effect and a substitution effect. In addition to giving incentive to change the scale of output, a change in the price of fuel gives incentives to substitute between fuel and other inputs, indicating that the cost of a fuel restriction policy relative to fuel expenditures is less than that of restricting the firm's output.

Comparing (16f) and (16c) indicates that whether a fuel restriction policy is cheaper than requiring emission control inputs depends on whether η_f is less than k. Since the formulas express costs as a per cent of fuel expenditures, the cost comparison also depends on the absolute level of fuel expenditures. The least costly of the four policies relative to fuel expenditures is emission regulation, which (16s) reveals to be a combination of the fuel restriction and control input policies. If the latter two policies happen to be equally costly, the emissions regulation will be half the cost of either of them.

As a further application, if the firm faces a perfectly elastic product demand and has a CES production function for output, evaluation of M and its cofactors gives $\eta_f = [1 - \epsilon + (\epsilon - \gamma)/(1 + p_f f/p_u u)]/(1 - \epsilon)(\gamma - 1)$ and $\eta_x = 1/(1 - \gamma)$ where the elasticity of substitution is $1/(1 - \epsilon)$ and the scale parameter γ is the percentage change in output that would result from a simultaneous 1 per cent increase in inputs u and f. For a short run situation, suppose the elasticity of substitution is zero ($\epsilon = \infty$). Suppose that expenditures on fuel and other variable inputs are each a third of the value of output, the total of the shares being substantially less than one due to short run fixity of many inputs. Assuming the shares add to the elasticity of output with respect to the inputs implying $\gamma = 2/3$, the costs of a fuel restriction and an output restriction policy are identical because of the zero elasticity of substitution assumption and are $a^2/3$ of fuel expenditures. For a long run situation, suppose that the elasticity of substitution is one ($\epsilon = 0$), fuel is a third the value of output, and other inputs are one-half the value of output with $\gamma = 5/6$. As a per cent of fuel expenditures, the costs of a fuel restriction policy are then $a^2/6$ and the costs of output restriction policy are $5a^2/24$. If k is 5, costs relative to fuel expenditures of a policy of requiring emission control inputs are $a^2/10$. The costs of emission regulation relative to fuel costs are $a^2/13$ in the short run and 1/8 in the long run. These examples illustrating how factor substitution and scale effects determine policy costs are consistent with the idea that costs rise with increasing rapidity as emission reduction approaches 100 per cent, in view of the a^2 term.

Relevance

This section has dealt with production theory for a firm under restrictions, in contrast to previous studies in which information about specific control devices and fuels has been used to estimate dollar costs at a point assuming no substitutions, for example the two studies done by the U.S. Environmental Protection Agency in 1963 and 1970. In future work it would be most useful to draw on details in engineering and physical science studies to estimate emission and output production functions, thus obtaining refined measures of substitution and scale effects.

Each policy type has many examples, all in need of the analysis contained in this section. The proposed tax on sulfur dioxide emissions is an example of the least costly of the four policy types. The major approach to air and water pollution followed in practice is of the same general type in that it deals with emissions. In the emission relation (11), there is a positive relation between polluting inputs and emissions. The common practice is to vary emission standards in line with this relation, allowing larger plants to pollute more than small ones so as to constrain every plant to emissions proportionally below the uncontrolled level. The standards are designed to force firms to adopt the more expensive control devices presently manufactured for each scale of output. This practice could be optimal economically in the special case where plants regardless of size are forced to equally high marginal costs of control and where damages from an extra pound of smoke are the same regardless of plant size. While the special case is probably never encountered exactly, the common practice is almost surely more optimal than setting standards invariant to scale.

For automobiles, the tax on leaded gasoline, requirement of catalytic mufflers, and emission standards or tests for cars, are examples of fuel input, control devices and emission policies. Limiting auto use in central business districts is an output policy, specifically restricting auto travel output.

The static case considered in this section provides a starting point for dynamic extensions in which policy costs are conceived as a present value. In view of incentives to move toward new factor combinations, enhanced inducements to discovery will lead to research and development responses to policies neglected in previous estimates of costs. Since substitutions depend on the wearing out of equipment, the optimal timing of pollution reduction depends on capital replacement decisions. Capital replacement analysis is needed for variances granted in judicial and administrative proceedings that allow delay in meeting standards. London laws banning coal in space heating provide examples of input policies with dynamic dimensions. Coal has been declining as a household fuel due to relative cost changes. Replacement of existing furnaces determines the timing. Part of the costs of reducing coal air pollutants is the present value of switching out of coal sooner rather than later.

Net Benefits

Best

The production functions considered so far have included equation (2) $y = y(z, q)$ explaining the output of commodities affected by pollution, equation (8) $x = x(u, f)$ explaining output of commodities whose production causes pollution and equation (11) $s = s(f, c)$ explaining pollution emissions. The system is completed by another production function

$$q_i = q_i(s_1, \ldots, s_n), \tag{17}$$

showing how pollution emissions are transformed into changes in the public good causing pollution damages. This function differs for air, water and solid wastes, and for pollutants within any one of the waste forms. It can indicate how treatment facilities affect q and how emissions s at one time affect the public good at later times. For the air pollution examples in this paper, (17) is an air dispersion model. As will be shown later, the effect of an emission s_j on air quality q_i within the same shed varies depending on the location of j and i.

If there is only one x and y producer each or if producers are identical with no locational differentiation within the shed, (17) reduces to $q = q(s)$. This equation can be used in expressions for y benefits such as (5) and (6) to replace q with s. One obtains benefits from y as a function of s which can be compared with the benefits from x as a function of s derived in the preceding section. In Figure 3, the y benefits as a function of s reach a maximum to the left of the maximum for the x good. Proceeding from the y maximum, the marginal y benefits are negative as s increases. The marginal y benefits with changed sign are marginal costs which may be plotted in the same quadrant as the marginal benefits from x. The marginal cost schedule is upward sloping and crosses the marginal benefit schedule for x still to the left of s_m. If the two marginal schedules are linear, the gain from moving from the free market situation s_m to the maximum net benefit point, say s^*, where the two marginal benefit schedules cross, is the area between the schedules or $-[b(y)_s^{s_m}]^2/2[b(y)_{ss}^{s} - b(x)_{ss}^{s}]$, where $b(y)_s^{s_m}$ is the y benefit from a unit increase in emissions at the free market level. The foregoing gain is the maximum potential gain from an environmental policy. Solving for the level of emissions where marginal benefits equal marginal costs and subtracting from free market emissions gives reduction in emissions necessary to achieve the maximum gain.

Absolutely inferior

If emissions are reduced beyond what is necessary to achieve the maximum gain, a level $\bar{s}$ will eventually be reached below which net benefits are less than at the free market level. With linearity, the critical emission reduction is twice the reduction necessary for maximum potential gain, or

$$s_m - \bar{s} = 2b(y)_s^{s_m}/[b(y)_{ss}^{s} - b(x)_{ss}^{s}], \tag{18}$$

that is, twice the marginal effect of emissions on y benefits at the free market level, divided by the sum of the slopes of the marginal schedules. Nonlinearities might increase negatively on the slope of the marginal benefits schedule for y at higher emissions and increasing marginal costs of control for x at lower emissions. Since the nonlinearities have opposite effects on s^* and $\bar{s}$, they could conceivably be offsetting. These considerations indicate information needed to eliminate policies, that may be put forth in the course of policy deliberations, which are worse than no policy.

Waste interfaces

An illustration brings out the economics of the much discussed possibility that reduction of one externality may increase another. Suppose a choice is being made whether to get rid of garbage by incinerator or landfill. Direct costs per ton of garbage are $10 for incineration and $6 for landfill. To estimate external costs, suppose the volume to be handled of 500 tons per day, if incinerated, would result in 10 tons per day of particulate emissions. If damages from the particulates increase by $10,000 for each increase of one ton in daily particulate emissions, the external cost of the incinerator is $100,000 per year. Assuming a total of 125,000 tons are handled during a year, the external cost for incineration is $.80 per ton of garbage. A landfill will impose external costs on surrounding residences due to unsightliness, smell and noise. For this volume of waste, assume a landfill would impose an average property volume loss of $2,000 on 1,000 residences or $2 million capital loss which implies a yearly loss of perhaps $200,000. The external costs for landfill are then $1.60 per ton. Direct plus external costs per ton are $10.80 for incineration and $7.60 for landfill. The external costs do not reverse the ranking based on direct costs in this example, but, of course, they ought in other cases.

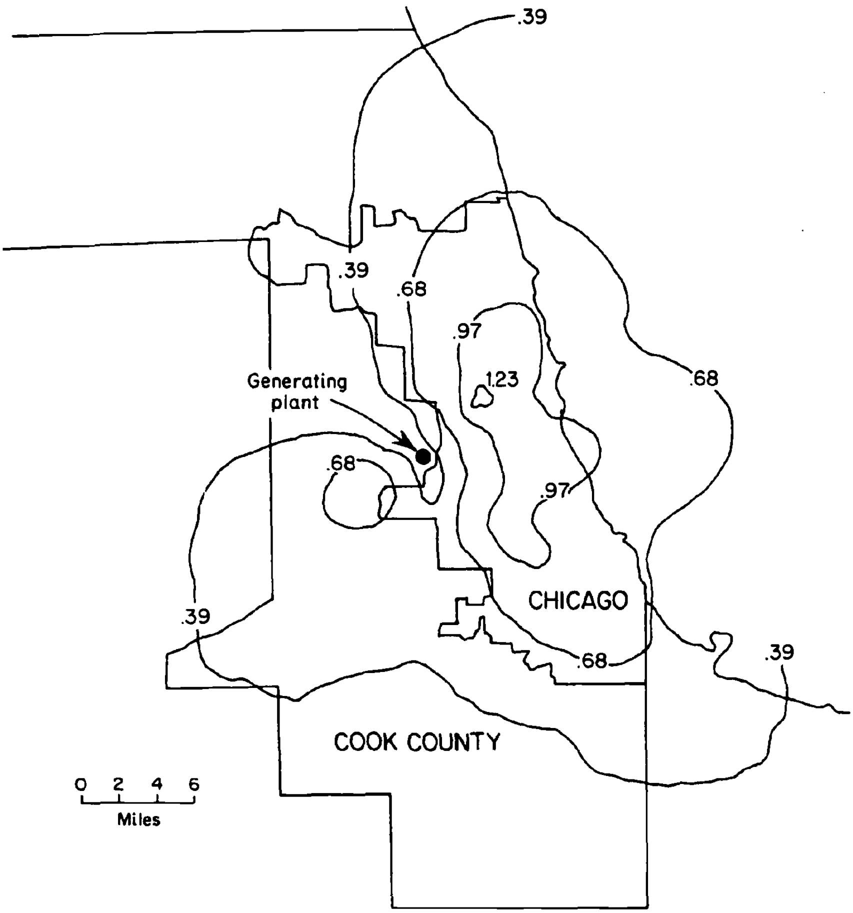
The landfill with external costs concentrated on a few residences in a vocal outlying community, might generate greater public opposition than the incinerator causing the landfill to be rejected in spite of its cost advantage. Requiring one payment for all compensation could make incentives of damagers and damagees coincide with incentives to maximize net benefits. If compensation of $2 million to surrounding property owners were required on opening the landfill (and likewise compensation to those damaged by air pollution were required if the incinerator were built) the external costs would be borne by those disposing of wastes. The damaged parties being fully compensated would lose their economic incentives for opposing the facilities.

Uniformity Losses

Within a metropolitan area, identical polluters cause different damages. Figure 4 shows SO_2 changes within the Chicago area that would result from a new power plant. The damages from the plant depend on densities of activity along each isopleth. Locating the plant differently would

Figure 4

Increase in SO_2 Levels from a New Generating Plant ($\mu g/M^3$)



change the isopleths leading to different damages. In outlying low density areas, the damages would be smaller.

Imposing uniform restrictions on emissions regardless of location imposes identical control on different externalities. All the current policies mentioned in the section on pollution control costs have this defect. Control may result in positive net benefits for some sources, while for other sources emissions are restricted below $\bar{s}$ with control costing more than worth. If quantitative restrictions are to be used, a case can be made for administrative or court regulation set case by case according to damages, rather than having a uniform emission standard. A uniform tax on emissions also imposes identical incentives on different externalities. To avoid the uniformity losses, the tax rate on emissions should vary at different points in the city. Salable emission rights also encounter the problem. If sales of rights to emit were allowed unrestricted within the metropolitan area, their trading value would tend to be the same as the tax necessary to attain the same level of emissions. With salable emission rights, *transfer fees* or *rebates* might be desirable equal to differences in damages caused by a change in the location of emissions.

Uniformity losses could be restricted by establishing zones within cities, within which uniform incentives would be imposed. Zoning could avoid a failure, possible under the foregoing policies, to find gains from eliminating pollution from some areas altogether. Joe Reid has emphasized the implications of nonconvexities, indicating a formal case for zoning to exclude some types of pollution altogether if the marginal damages are decreasing rather than increasing. The stability conditions are then violated, and the market—or policies trying to correct the market marginally—may find a local polluting optimum where net benefits are less than with no pollution. The normal concave situation of increasing marginal damages probably applies to materials damages and health. The convexity argument applies to esthetic and recreational uses of land, whereby a little bit of blight is sufficient to reduce drastically the benefits and with further blight not having much effect after the initial impact.

None of the policies mentioned so far avoids the free rider problems of getting people to bid either for reduced pollution or for the generation of knowledge about health and other adverse effects of pollution. Schemes have been proposed, so far at an abstract level, for including people to reveal their preferences for a public good by making the supply curve facing them be the actual supply curve less other people's bids (Clarke, Tideman). These schemes face the same problems connected with nonuniformities as do other policies.

The issue of losses from uniformity extends beyond spatial variation within one metropolitan area. When the wind is blowing and the weather is mild, reducing demand for fuels for heating, the marginal damage caused by a given level of emissions may be small, in contrast to great damages in still, cold weather, and even greater damages during an inversion. If a single emission standard must be observed at all times, as most plans require, different external costs are being treated alike over time as well as over space. Emergency measures required during episodes are a step in the direction of recognizing uniformity losses.

Administrative costs and regulatory behavior partly determine how much uniformity should be imposed, but the benefits and costs being considered in this paper also influence the choice. Because there are costs of varying the level of emissions, particularly if plants must be shut down for temporary periods, the maximization of net benefits does not call for instantaneous adjustment of emissions to every change in external costs.

The uniformity issue is particularly severe for automobiles in view of the variability in their emission damages with weather and traffic. While the costs of instantaneous adjustments appear prohibitive, the current legislative approach aiming to require the same control at all times everywhere maximizes uniformity losses. Preliminary results by Richard Zerbe suggest promise for varying standards by area and other intermediate strategies.

Location of Industry in Different Parts of the Country

Applying the same emission standard everywhere in the nation carries uniformity losses to a maximum. Costs for areas where emissions are reduced below $\overline{s}$ could exceed gains for areas of positive net benefits. If an industry's production costs are not very different among locations, shifts toward areas of low damage may be cheaper than relying solely on control in place. One of the least costly ways to reduce pollution losses could be to induce a different locational pattern. At odds with this idea is current legislation, which aims to freeze location. Standards for new plants are the same everywhere and are more stringent than for existing plants, impeding even normal locational adjustment.

While prominent in classic externality discussions (Coase, Pigou) spatial considerations have not been fully resolved partly because of need to more adequately consider land. The usual conclusion that a quantitative restriction, tax or salable right have the same effects on a producer is valid only if he stays in business at the same location. Consider the bid for an industrial site by a polluter. He will have higher profits with a quantitative restriction on emissions requiring no payments, than he will with necessity to pay an emissions tax, even though the two forms of control induce the same emissions reduction if he produces at the site. With the quantitative restriction he can bid more for the site and is more likely to bid out competing users. To foster optimum allocation, it appears his tax payments should equal total damages imposed making his bid correctly reflect x-benefits less y-losses. In deciding where to locate, externalities will then be internalized.

One pitfall to avoid is levying only a marginal tax rate. If an emission tax rate is made equal to marginal damages caused by a pound of pollutant, the total tax paid will equal total damages only if marginal and average damages are equal. If the idea is correct that marginal tends to be above average damages, the tax collected would be greater than total damages calling for a lump sum rebate. Under any policy, there may be a difference between marginal payments for emissions and the damages caused. As another example, under an emission standard marginal payments are zero. A general rule is to make lump sum rebate (or tax) equal to the difference between the sum of marginal payments and the total damages caused.

Payments by polluters should be coupled either with no compensation to those damaged (Baumol) or more equitably one payment for all compensated. As applied to land values, with no compensation, external costs will cause negative windfalls to owners of land on which external costs are borne, and taxpayers will gain the proceeds of the tax. With compensation, there need be no such wealth transfer. The present value of the damages is transferred from polluters to owners of affected land exactly offsetting the loss in sale value of their land due to the damages. Note that compensation is not related marginally to damages and is to be paid to land owners, not land users. If frequent compensation is expected and if land owners can manage to have excessive losses incurred on which to base the compensations, the expectation of compensations might conceivably induce nonoptimal use of land on which damages occur. However, the idea of deciding land use for expected compensation ignoring market revenues seems somewhat far fetched, and the practice would be limited by abilities of outside adjudicators to verify gross cases of excessive losses.

With agreement that the foregoing norms would induce optimal adjustment to pollution, estimates of costs of departures from them could be made. This requires comparing locational differences in costs of polluting production with differences in damages, a job in which little progress has yet been made.

Conclusion

Any environmental policy instrument reduces pollution damages through some combination of reducing emission producing inputs, installing pollution control devices, reducing product output or changing the location of activities. This paper has examined benefits and costs for these dimensions. Instead of seeking a single best instrument the approach has been to compare alternatives, recognizing that resource allocation is not the sole consideration in environmental policy. Yet the very reason for concern with the environment is to correct resource allocation failures. Resource allocation is more important in environmental policy than in many other policy areas.

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COMMENT

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It is common knowledge that the best level of pollution occurs when the marginal damage of pollution offsets the marginal cost of an action which reduces pollution. This rule can be characterized either graphically or mathematically. The first sections of George Tolley's paper provide us with an original treatment of some thorny conceptual issues involved in identifying these functions.

It is also true that goods or bads, as the case may be, have a space and time dimension. Carrots from the San Joaquin valley differ in a fundamental economic sense from carrots from Chicago, and the economic value of a given environmental quality level in New York City only fortuitously is the same as the level in the desert region of Utah. Therefore, most would agree that a uniform air or water quality standard is not likely to make economic sense. The fourth and fifth sections of the paper discuss the effects of uniformity, those heavy-handed environmental policies which fail to recognize the spatial and temporal characteristics of bads.

The necessary ingredients for evaluating alternative environmental policies are benefit and cost functions. In too many publications, empirical benefit functions capture the value of changes in environmental quality by looking only at changes in the total expenditures of variable factors. Such estimates are conceptually biased, since changes in environmental quality impinge on the value of producers' and consumers' surpluses, necessary elements in the true estimate of net benefits. For plausible values of the elasticities of demand and supply the bias is shown to be significant. Tolley's main contribution here is to treat households as firms after the fashion of Becker.

Turning next to loss functions, the analysis begins with single product profit maximization in an environment where pollution occurs but voluntary regulation is ruled out. The first point of departure assumes a control policy on emissions. Since the control policy is restrictive—otherwise why have it?—benefits are reduced compared to the unregulated market outcome, reduced by the marginal cost of control. Labels may be misleading. The focus is on the production of conventional goods in combination with bads. Forcing firms to produce less bads increases their costs, referred to in the text as change in benefits. It should be emphasized that the author is not here discussing what is commonly referred to in the literature as the benefit or damage reduction function.

The regulator's second policy alternative involves the choice of a level of control inputs. It is exemplified by the prescription: Use secondary treatment in the case of water quality management. For any given level of control input, the optimal level of the pollution intensive input will be greater in the second policy relative to the first unless it is in a world of fixed factor proportions. As long as factor substitution is technically feasible, policy two is second best, involving greater private costs for any given initial level.

A third policy requires regulating the level of the pollution intensive input, while the fourth policy entails controlling emissions by using a final output level.

Emission regulation is superior to all other policies because the entrepreneur is left with more choice. He can select best values for x, f, c, and u whereas with the remaining policies, one of the first three variables is exogenously determined. Tolley proves that policy three, restricting pollution intensive inputs, is superior to the output restriction policy four after assuming a constant marginal benefit (loss) function and a specific form for the emission relation (11). The same conclusion holds much more generally. The policy which has the flattest marginal benefit function (3) is best. Therefore, if the fuel restriction policy is better than restricting output,

$$b(x)_{ss}^{\bar{f}}/b(x)_{ss}^{\bar{x}} < 1,$$

where $b(x)_{ss}$ is the slope of the marginal benefit function. Since

$$b(x)_{ss}^{\bar{f}} = (1/S_f^2)(M/M_{ff}), \qquad (15f)$$

$$b(x)_{ss}^{\bar{x}} = (1/S_f^2)(M_{xx}/M_{xf})(M/M_{xf}), \qquad (15x)$$

using the original notation, then

$$b(x)_{ss}^{\bar{f}}/b(x)_{ss}^{\bar{x}} = \frac{M_{xf}^2}{M_{ff}M_{xx}} < 1$$

or

$$M_{ff}M_{xx} - M_{xf}^2 > 0.$$

One can show that this expression indeed is positive by computing its value from the determinant exhibited above (11) in the original paper. The only requirement is that the production function is concave.

Regrettably, a complete general ranking does not seem possible since the virtues of the fuel policy (3) relative to the fixed control expenditures policy (2) depend on the choice of elasticities and parameter values.

The last pages of Tolley's paper discuss some of the problems which arise when a uniform policy is applied to an area or time period in which the net benefit function varies. Uniformity of pollution policy is expensive because no longer are there incentives to make intertemporal production adjustments or substitutions from a region of high opportunity cost to one of low opportunity cost of pollution.

Zoning and salable rights are additional tools available to policy makers. As the author rightly emphasizes, if the rights are not well-defined in space, the rights will be distributed inappropriately unless exchange involving spatial transfer is accompanied by a charge which reflects spatial opportunity cost differences.

This section offers fertile ground for other investigators to till. To cite one example, suppose meteorology was a fine-tuned science enabling us to predict weather with certainty. Suppose weather changes affect the net benefit pollution function and policy-makers had chosen a policy of charging for emissions. What is the optimal rate of price change? Surely economists would not recommend changing price with each change in the weather. Nor would they likely recommend no price change. Where on this broad spectrum does the correct rule, in fact, lie?

In the first section, benefits due to a change in pollution level, correctly measured, are the changes in the variable factor cost plus changes in profit plus changes in consumers' surplus. In the second section, the cost to producers of changes in the level of pollution is equal to the change in profits. It appears that there is double counting with changes in profit showing up in both the benefit and cost function. This is false. Note that the arguments of the benefit function are pollution level and commodity y referred to in one place as a thinness of dust cover. In contrast, the costs are due to changes in profit from producing commodity x and pollution (more accurately, emissions). Since one component in the objective function in the second section is the total consumers' surplus of x which is distinct from good y, there is no double counting. Tolley finds it helpful to structure his analysis of the net benefits of environmental policies in a unique fashion. For this effort he deserves credit, but if he would provide travelers with a few more signposts along the way, he would reduce the cost of the trip and gain more adherents to his preferred route.

In section five, Tolley cautions policymakers to avoid using *marginal* tax rates. When marginal damages are above average damages, he reasons, total tax take will be greater than total damages, calling for a lump sum rebate. There may be arguments, stemming from distributive concerns, why total taxes ought to equal total damages, but efficient resource allocation calls for marginal rules and air resources are not an exception. If I wish to buy an additional unit of air quality, surely I should pay its "owner" his opportunity cost. If he is a wealth maximizer, surely he will not sell that unit on the basis of the average value of all units in his stock of wealth.

What types of problems are amenable to Tolley's formal analysis and in what problem setting do his general results hold? His story is cast within the framework of the short run and there is no uncertainty. Only one pollutant exists thus disposing of the problem of synergism in production and consumption. Consumers have access to the best available knowledge as do producers and they respond to changes instantaneously. Producers are profit maximizers where the latter notion is given a simple straightforward textbook interpretation. The cost of actualizing and maintaining each policy is the same. Policies do not differ with respect to political feasibility, administrative ease, difficulties of enforcement and other factors discussed in the companion piece by Baumol and Oates.

Some may wish to argue that Tolley cast his net in too modest an arc. I would argue that even artificially simple but sound approaches are meritorious because they place in bold perspective crucial relationships which may change only in degree when a more encompassing model is developed. Understanding of the complex generally proceeds from a deep appreciation of the less complex to which this paper is a contribution.

Tolley is engaged in a substantial research project on environmental quality. This paper probably can be regarded as an interim report in which the author spells out the analytical framework of the larger study. Some of the topics are better developed than others, leaving the reader with an impression of rugged terrain rather than a polished surface. Nevertheless, the paper is a provocative and original contribution to the literature on environmental quality and bears the imprint of an insightful innovative mind. With this paper as openers, I'd bet heavily on the final study.