Emission Taxes when Pollution Depends on Location*

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Abstract

We consider the Pigouvian tax as a means to regulate polluting activities which social cost decreases with distance from a given location. We show that such a tax must explicitly adjust for distance if and only if polluters hold some market power. In this case, furthermore, the tax may not decrease monotonically in both distance and market power.

Keywords: Pigouvian tax, spatial taxes

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1. Introduction

To the extent that the external costs associated with certain polluting activities depend on the area where such activities take place, one reasonably expects optimal corrective measures to take spatial information into account. Indeed, Tietenberg (1974), Hochman et al. (1977), Henderson (1977), Hochman and Ofek (1979) and others emphasized early on that policy instruments, notably taxes, should explicitly consider local features when these influence the amount and impact of polluting emissions. Over the past 30 years, a number of studies in the fields of urban/regional and environmental economics have pursued this line of investigation.[1] Some theoretical contributions, such as Xepapadeas (1992) and Uimonen (2001), seeked to develop sophisticated price instruments. Applied works, on the other hand, often built on novel technologies, such as Geographic Information Systems (GIS), which are now helping environmental economists to collect and use spatial data.[2]

At this point, however, the literature has ignored the additional distortions that may be induced by some polluters' market power. This paper's raison d'être is therefore to study how market structure affects the Pigouvian tax rule when pollution externalities vary with distance. In the manner of Buchanan (1969) and Barnett (1980), we consider two polar types of market structure: perfect competition and monopoly. As will be seen, the optimal tax rule ignores distance in the former case (where polluters have no market

[1] For an excellent review on spatial land use, see Bockstael and Irwin (2000) and Hardie et al. (2004). Works drawing instead on Hotelling's (1929) seminal linear-city model are also carefully surveyed by Gerking and List (2001) and Geoghegan and Gray (2005).

[2] Bateman et. al. (2006) provides a good survey of GIS applications.

power), but it explicitly trades off distance and market power in the monopoly case.

The paper unfolds as follows. The upcoming section presents the model. Spatial Pigouvian taxes when polluters are price-takers are derived in section 3. Section 4 next considers the case of a single monopolistic polluter. Section 5 makes concluding remarks.

2. The model

Consider the stylized landscape represented in Figure 2.1. It is composed of a continuum of polluters located along a line of total length ℓ, and some affected party (pollutees) situated at the extreme left-hand-side. The latter location, which we associate with that of a city/urban center and marketplace, is labelled as the origin (0). The variable x denotes the distance between polluters and pollutees.

In this model, the magnitude of the externality caused by a specific polluting activity depends on the latter's location x. To fix ideas, one may think of noise, smells, light, or any similar urban nuisance, or of the soil erosion and sedimentation provoked by farming activities along a river that feeds a city's water reservoir located at the origin (0).

2.1. Polluters

Assume all polluters deliver a homogeneous output, and denote $z(x)$ the output of a polluting firm/individual situated at (x). Total production is thus given by

$$\mathbf{Z} = \int_0^\ell z(x)dx \tag{1}$$

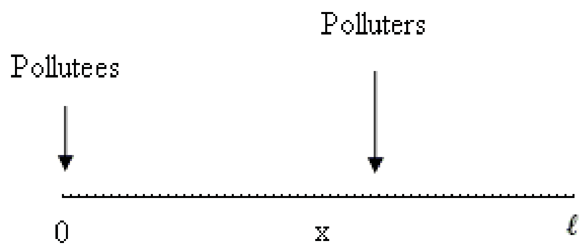

Figure 2.1: The landscape

At output level $z(x)$, the corresponding firm incurs a cost $C(z,x)$ which depends on its distance away x from the market. This cost function is strictly increasing and convex in both z and x, and the cross derivative C_{zx} is strictly positive. Convexity in the distance x, and the assumption that the marginal cost of production increases in x, mean that firms located farther from the market suffer increasing transportation and marketing costs.

Suppose that a firm's contribution to the disamenity is captured by the function $f(z,x)$ which is increasing and convex in z. This reflects the fact that pollution grows at an increasing rate with production. On the other hand, let $f_x < 0$ and $f_{zx} < 0$. The latter indicate that, all things equal, external damages are less important when the firm is more distant from the population center. To keep things tractable, we assume that a firm's pollution does not affect other firms' production. The overall level of pollution is thus given by

$$E = \int_0^\ell f(z,x)dx \tag{2}$$

Let us now turn to the affected party.

2.2. Consumers

People located at the origin (0) will consume all the firms' production Z. Let $p(\mathbf{Z})$, with $p'(\mathbf{Z}) < 0$, denote their aggregated inverse demand. They also endure a disamenity $a(E)$ which increases linearly with the level of pollution, i.e. $a = vE$ with some positive coefficient v.

We shall now first compute the optimal emission tax in this setup in a context where firms are price-takers.

3. Market structure 1: perfect competition

In the absence of pollution taxes, each firm maximizes profits given by

$$\pi(z) = pz - C(z, x) \ ,$$

so its marginal cost must match the market price

$$p(\mathbf{Z}) = C_z(z, x) \ .$$

Since this marginal cost increases with the distance x from the market (recall that $C_{zx} > 0$), a more remote firm delivers less output. This situation is depicted in Figure 3.1 (assuming a quadratic cost function).

It follows that the derivative $z_x < 0$.

If a positive tax t per unit of pollution/disamenity is imposed, on the other hand, a

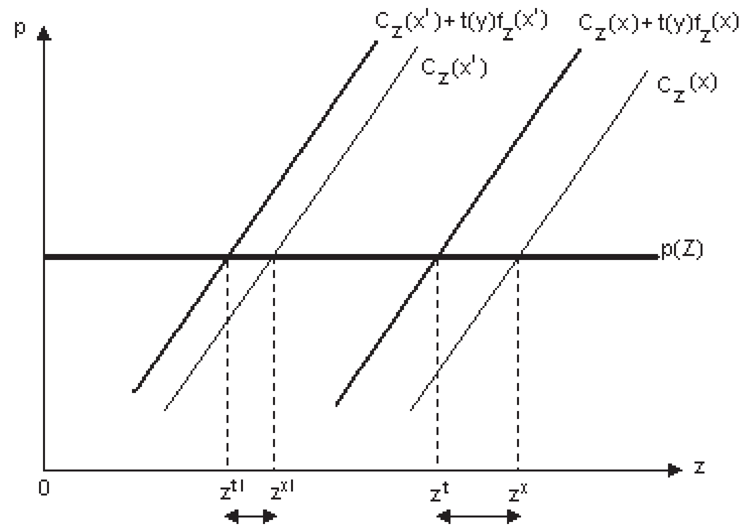

Figure 3.1: The effect of taxation on marginal costs ($x\prime > x$)

firm situated at x will maximize the profit function

$$\pi(z) = pz - C(z,x) - t \cdot f(z,x) \ ,$$

thereby setting its production level in order to satisfy the first-order condition

$$p\left(\mathbf{Z}\right) = C_z + t \cdot f_z \ . \tag{3}$$

Satisfying (3) entails of course that the output goes down as t goes up.

Let the corrective tax be set by a benevolent and informed regulator who therefore seeks the largest sum of consumer surplus and producer benefits minus the social disamenity. Ignoring redistribution and income transfer issues, and replacing E by the right-hand-side formula in (2), the tax should then maximize

$$W = \int_0^{\mathbf{Z}^t} p(u)du - \int_0^{\ell} C(z^t, x)dx - v\int_0^{\ell} f(z^t, x)dx \ , \tag{4}$$

where the superscript t refers to the farmers' adjusted output once they bear the tax. The necessary and sufficient first-order condition for an optimal policy is now

$$W'(t) = \int_0^{\ell} \left(p(\mathbf{Z})\frac{dz}{dt} - C_z\frac{dz}{dt} - vf_z\frac{dz}{dt} \right) dx = 0 \tag{5}$$

The latter holds only when

$$p(\mathbf{Z})\frac{dz}{dt} - C_z\frac{dz}{dt} - vf_z\frac{dz}{dt} = 0 \tag{6}$$

is true at every point $(x) \in [0, \ell]$ (but on a set of Lebesgue measure 0).[3] Substituting (3) into (6) yields the general formula for the optimal tax rule:

$$t = v \ . \tag{7}$$

This is precisely the original Pigouvian tax, which is set in order to meet the marginal social disamenity. This rule seems to neglect an important piece of geographical information, since firms with different locations face the same tax t. Under such a rule, however, expression (3) becomes

$$p(\mathbf{Z}) = C_z(z, x) + tf_z(z, x) \ .$$

[3] This step is authorized by the fact that the integrand in (5) never changes sign over $[0, \ell]$. Were this the case, the market price would not always cover marginal cost, so some firms would abandon production while others would stay. This cannot happen in the present model.

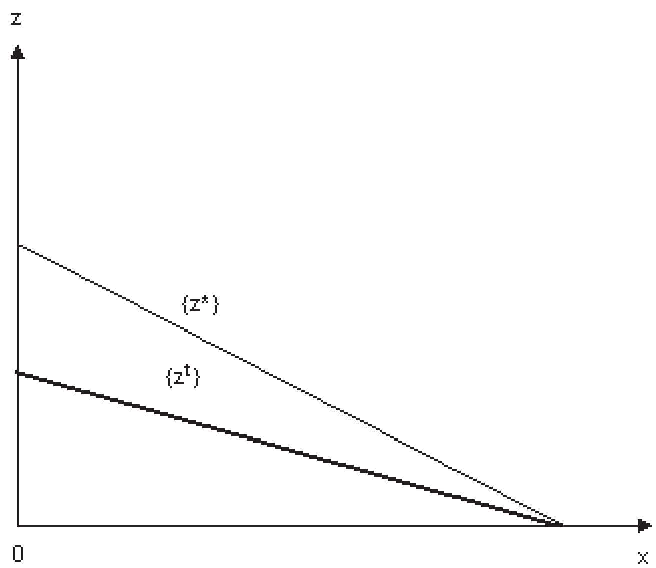

Figure 3.2: The effect of taxation on production distribution

Since the marginal contribution to pollution f_z decreases in x, a more distant firm needs to adjust proportionally less than one that is located closer to the market. More productive firms are thus penalized the most. In other words (see Figure 3.2), the main effect of this tax is to render the distribution of the outputs $z(x)$ flatter.[4]

Proposition 1. *In the absence of market power, the optimal pollution tax ignores spatial information.*

This result indicates that price-taking polluters will be subjected to the same corrective tax regardless of their 'geographic' responsability. We shall now address the situation

[4] Another possible consequence might be to force the farther and less productive producers to exit the market. We do not consider this issue here, as it would make total industrial or farmland endogenous to the optimal taxation problem.

where firms have market power, considering the polar case of a polluting monopoly[5].

4. Market structure 2: the monopoly

Suppose now that all firms in the present landscape (urban or rural) collude to form a monopoly.[6] Their objective is thus to maximize joint profits

$$\Pi(\mathbf{Z}) = p\left(\mathbf{Z}\right)\mathbf{Z} - \int_0^\ell C(z,x)dx - t\int_0^\ell f(z,x)dx \ .$$

In this case, the production level of every unit (x) must altogether satisfy the following first-order condition

$$\int_0^\ell \left[p'(\mathbf{Z})z + p(\mathbf{Z}) - C_z - tf_z\right] dx \ = 0 \ . \tag{8}$$

This requires that

$$p'(\mathbf{Z})z + p(\mathbf{Z}) - C_z - tf_z = 0 \tag{9}$$

at every point $x \in [0,\ell]$ (but on a set of Lebesgue measure 0).[7] Substituting (9) into (6) then yields the general formula for the optimal tax per unit of pollution:

$$t(x) = v + \frac{p'(\mathbf{Z})z\frac{dz}{dt}}{f_z\frac{dz}{dt}} \ . \tag{10}$$

[5] The main qualitative implication of our model remain valid under an oligopoly.

[6] This means that the productive landscape is managed as one business entity. Therefore, in this section, the meaning of location (x) is slightly different than in the competitive case. For instance, here location (x) can be simply interpreted to be a farming plot in a rural setting (or a plant in an urban one) instead of an individual farmer (firm). Subsequently, all profit redistribution issues become an internal managerial problem.

[7] This is true by an argument similar to the one stated in footnote 1.

The second term on the right-hand side of this formula is an amendment to the tax rule that was proposed in the previous section. It is negative, so the new tax rate is actually smaller. This agrees with the classical results of Buchanan (1969) and Barnett (1980). The underlying intuition is now well-known: when polluters are not price-takers, the optimal corrective tax must be set lower than the marginal social cost of damage in order to alleviate the consequent strategic reduction in output. Expression (10) can in fact be rewritten as

$$t(x) = v - \frac{\frac{p(\mathbf{Z})}{|\varepsilon|} \frac{z}{\mathbf{Z}} \frac{dz}{dt}}{f_z \frac{dz}{dt}} \ ,$$

where ε denotes the price-elasticity of demand. As demand becomes less elastic, the size of the downward adjustment tends therefore to increase. This property limits the exercise of market power by the monopolist and prevents consumer surplus from falling too drastically.

With respect to the literature on Pigouvian taxation, however, formula (10) exhibits a peculiar feature: its downward adjustment term takes into account the respective impacts of each field/plant according to its location.

Comparative statics with respect to the spatial coordinate x implies that

$$\frac{\partial t}{\partial x} = p'(\mathbf{Z}) \left(\frac{z_x \left(f_z - z f_{zz} \right) - z f_{zx}}{\left(f_z \right)^2} \right) \tag{12}$$

The sign of (12) depends on the sign of $A = z_x \left(f_z - z f_{zz} \right) - z f_{zx}$. Straightforward manipulations reveal that

$$A \lesseqgtr 0 \Leftrightarrow \frac{z_x}{z}(1-\eta) \lesseqgtr \frac{f_{zx}}{f_z} \Leftrightarrow \frac{\partial t}{\partial x} \gtreqless 0 \tag{13}$$

where $\eta = \frac{f_{zz}}{f_z} z$ is the elasticity of a plant's (farm) marginal contribution to pollution with respect to output z. This supports the following proposition.

Proposition 2. *In the presence of market power, holding everything else constant, the regulator must increase (decrease) the pollution tax when the spatial coordinate x of a plant (farm) goes up if and only if the adjusted rate of change of output with respect to distance from the pollutees $\left(\frac{z_x}{z}(1-\eta)\right)$ is smaller (larger) than the rate of change of the marginal contribution to pollution with respect to distance from the pollutees $\left(\frac{f_{zx}}{f_z}\right)$.*

The elasticity coefficient η spans in fact two distinct intervals. In the high range where $\eta > 1$, the marginal contribution to pollution is very responsive to output. We have from (13) that

$$\frac{z_x}{z}(1-\eta) > \frac{f_{zx}}{f_z} \Leftrightarrow \frac{\partial t}{\partial x} < 0 \ ,$$

so the optimal pollution tax must decrease in the distance x unambiguously. In the inelastic range where $0 < \eta < 1$, i.e. when the marginal contribution to pollution is not too responsive to an increase in output, on the other hand, the trade-off highlighted in our proposition holds. If output $z(x)$ drops by a larger amount than the marginal contribution to pollution for a given increase in the distance x from the urban center/market, then the optimal pollution tax is set to *augment* with x. In this case, the tax rule provides reduced incentives for the monopoly to shift production from closer plants/farms to farther ones, where larger production costs will translate into higher prices for consumers with relatively little compensation on the environmental side. The opposite occurs when the marginal contribution to pollution drops by a larger amount than production as x increases: the optimal tax is set to decrease with the distance x, for the positive impact on welfare of shifting production away from the urban center/market outweighs the negative impact this has on consumer prices.

5. Concluding remarks

This paper studied an emission tax meant to regulate polluting activities which impact is inversely related to distance from a given point. The upshot is that such a tax should be location-dependent only when polluters have market power. In this case, it should be proportional to the social cost of pollution, and should also depend on observables such as local productivity and distance from the affected parties.

The present analysis could be extended in various directions. Dealing with other market structures, such as monopolistic competition, is perhaps the most obvious one. Land rents and location could also be made endogenous, which would require a general equilibrium framework.

Simple as it is, however, this paper's model might have several ramifications for environmental policy. For example, it might inform current discussions on "eco-conditionality," or whether and how much to reward farmers for their "environmental services" (such as safeguarding the beauty of rural areas and sheltering endangered species). To see this, note that the above tax t and environmental cost ν can be negative and correspond respectively to a subsidy and an environmental amenity enjoyed by urban citizens (which becomes smaller as it is generated farther away). If farmers collude (forming a cooperative or some powerful association), then proposition 2 recommends to base individual grants, not only on the value of the provided environmental services, but also on distance and local productivity.

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