Spatial Environmental Economics

Lecture 2: Models, Environmental Externalities, and Regulation

Augusto Ospital

LMU Munich

May 7, 2025

Roadmap

1. Elements of Economic Models
2. Production Externality
3. Pigouvian Taxes
4. Command and Control Regulation
5. The Coasian Insight
6. Regulation in space

Roadmap

1. Elements of Economic Models
2. Production Externality
3. Pigouvian Taxes
4. Command and Control Regulation
5. The Coasian Insight
6. Regulation in space

Elements of economic models

- This lecture develops a simple model of firms with externalities
- There are typically three parts to any economic model:
  1. Exogenous model parameters or variables
  2. Endogenous model parameters or variables
  3. Equilibrium concept
- Later in this course we will discuss the typical components of a spatial economic model

Exogenous parts

- Exogenous model parameters are those elements of a model that are taken “as given”
- They do not respond to other elements of the model
- You, as an economist, can change their values to study how a change in an exogenous parameter changes the outcome of the model

Endogenous parts

- Endogenous model outcomes are the elements of the model that "move around"
- They are those elements of a model that respond both to exogenous elements and to other endogenous ones
- You do not get to choose values of endogenous variables. It is left for the model to predict their values
- Ultimately, we are interested in understanding how changes in an exogenous parameter result in changes to endogenous variables

Equilibrium

- The model equilibrium defines the “relation” between exogenous and endogenous elements of the model
- If such a relation exists and is unique, then the model has one and only one prediction
- The model prediction is the set of endogenous variables, given the exogenous ones, such that the equilibrium relation between these variables hold
- Typically, we formalize an equilibrium as the intersection of supply and demand

Models: right or wrong?

- A model is an analytical framework to address a set of questions. This means that we have to start from questions, then design models to address those questions
- Hence, a model is not right or wrong per se. Whether it is useful/useless, illuminating/misleading, applicable or not, depends on which questions we'd like to address
- Models are like knives. Every type of knife is designed to cut specific things such as fruits, bread, cheese, etc.

Models: simple or complicated?

- In another analogy, a model is like a map
- In one extreme, a map that is too simple cannot guide us to find required paths and addresses
- In the other extreme, a map that contains too much details will distract us by giving too much unnecessary information, so much so, that the map might not be useful anymore
- For example, to design a model to study the impact of a hypothetical U.S. carbon tax:
  - ... U.S. interactions with other countries?
  - ... that workers can switch across jobs?
  - ... that investment decisions may change?
  - ... that if workers are adversely affected will vote for polices that restore free trade?
  - ...
  - Where should we stop?
- A map that contains all realities should be as large as the real world!

Roadmap

1. Elements of Economic Models
2. Production Externality
3. Pigouvian Taxes
4. Command and Control Regulation
5. The Coasian Insight
6. Regulation in space

Production externalities

- Consider two perfectly competitive firms, neighboring to each other, but selling to different product markets:
  - Producer M (a manufacturing factory)
  - Producer A (an agricultural farm)
- A byproduct of the manufacturing factory is the pollution of the air and water in the area
  - The manufacturer does not suffer any consequence from pollution
  - Pollution is bad for growing agricultural products
- The unregulated market outcome does not put a price tag on the negative externality that Producer M generates for Producer A

Production externalities: model setup

- Producer M takes price p_M as given and chooses output quantities y_M to maximize profits

$$\pi_M = p_M y_M - C_M(y_M)$$

- Producer A takes price p_A as given and chooses output quantities y_A to maximize profits

$$\pi_A = p_A y_A - C_A(y_A) - D(y_M)$$

- $C_M(y_M)$ and $C_A(y_A)$ are the total costs of producing quantity y_M and y_A
- We assume that the marginal costs $C'_M(y_M)$ and $C'_A(y_A)$ are positive and increasing
- Function $D(y_M)$ measures the pollution **damages** suffered by A for a given output of M

Unregulated market output choices

- The first order conditions from M's profit max. problem imply marginal cost pricing:

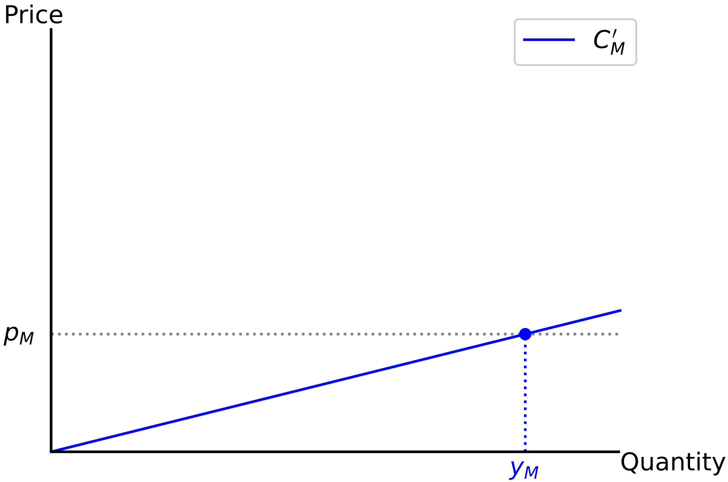
$$\max_{q_M} \pi_M(q_M) \quad \Longrightarrow \quad \frac{d\pi_M(q_M)}{dq_M} = 0$$
$$\Longleftrightarrow \quad C'_M(y_M) = p_M$$

  - I.e. marginal private cost = marginal private benefit
  - Determines the market outcome y_M

- Similarly for Producer A, the market outcome y_A satisfies marginal cost pricing:

$$C'_A(y_A) = p_A$$

Example: $C_M(y) = 0.5y^2$ and $D(y) = y^2$



Socially optimal outcome

- Now suppose we were to maximize the joint profit of the two producers:

$$\pi_M\left(y_M^\star\right) + \pi_A\left(y_A^\star, y_M^\star\right)$$

- Denote the socially-optimal output levels as $y_M^\star$ and $y_A^\star$
- The first order condition with respect to the manufactured good is

$$\begin{aligned} \frac{d}{dq_M}\left[\pi_M\left(y_M^\star\right) + \pi_A\left(y_A^\star, y_M^\star\right)\right] &= 0 \\ \iff C_M'\left(y_M^\star\right) + D'\left(y_M^\star\right) &= p_M \end{aligned}$$

  - I.e. marginal social cost = marginal social benefit
  - The marginal externality, $D'(y)$ measures the damage to producer 2 from an extra unit of y_M
  - We assume that the marginal damage is strictly positive and increasing

Market vs. socially optimal outcome

- Recap: market outcome (y_M) and socially-optimal outcome ($y_M^\star$) determined by:

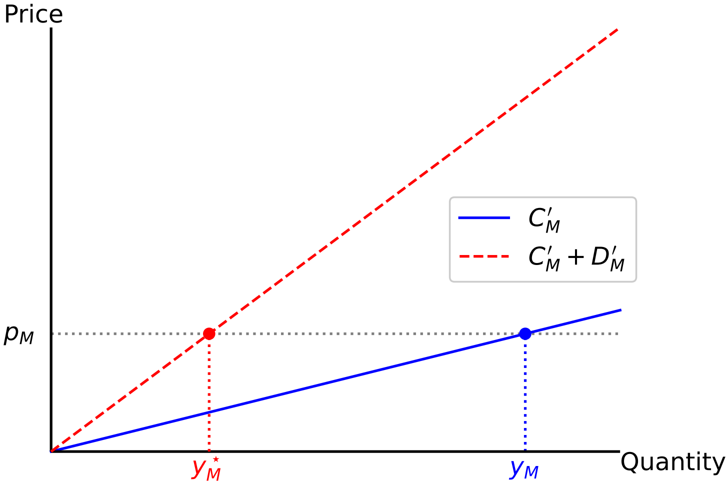
$$\begin{aligned} C'_M(y_M) &= p_M \\ C'_M(y_M^\star) + D'(y_M^\star) &= p_M \end{aligned}$$

- Since prices p_M are taken as given, we have $C'_M(y_M^\star) + D'(y_M^\star) = C'_M(y_M)$
- Since $D'(y_M^\star) > 0$, it must be that $C'_M(y_M^\star) < C'_M(y_M)$
- Since marginal costs are increasing, it must be that

$$y_M^\star < y_M$$

  - I.e., there is **over-provision** of the manufactured good in the unregulated market

Example: $C_M(y) = 0.5y^2$ and $D(y) = y^2$



Correcting externalities

Four key ways how regulation can restore the socially-optimal outcome:

1. Taxing the source of externality: **Pigouvian taxes**
2. Dictate the right amount of quantities: **Command and Control**
3. Create a market for pollution via property rights: **Coasian solution**
4. Create a market for permits: Cap and trade

In this lecture we discuss 1-3

Roadmap

1. Elements of Economic Models
2. Production Externality
3. Pigouvian Taxes
4. Command and Control Regulation
5. The Coasian Insight
6. Regulation in space

Pigouvian Taxes

- **Optimal Pigouvian tax**:

  A tax that equals the wedge (=difference) between marginal social cost and marginal private cost (evaluated at the optimal level of quantity)
- In our model:

$$\begin{aligned}\text{Marginal Social Cost}\,(y_M) &= C_M'\,(y_M) + D'\,(y_M)\\ \text{Marginal Private Cost}\,(y_M) &= C_M'\,(y_M)\end{aligned}$$

- Therefore

$$\begin{aligned}t^\star &= \text{Marginal Social Cost}\,(y_M^\star) - \text{Marginal Private Cost}\,(y_M^\star)\\ &= D'\,(y_M^\star)\end{aligned}$$

Output choice with per-unit tax t

- Producer M's profits are now

$$\pi_M^{tax} = p_M y_M^{tax} - C_M\left(y_M^{tax}\right) - t y_M^{tax}$$

  - y_M^{tax} denotes the choice when taxed
- The first order conditions for profit maximization are

$$C_M'\left(y_M^{tax}\right) + t = p_M$$

- Intuition: the tax is increasing the cost of producing an unit of manufactured good
  - Therefore correcting the over-provision

Optimal Pigouvian tax restores the socially-optimal outcome

- Now set the tax equal to the optimal Pigouvian tax:

$$t^{\star} = D'\left(y_M^{\star}\right)$$

- Replacing in the first order condition we obtain $C'_M\left(y_M^{tax}\right) + D'\left(y_M^{\star}\right) = p_M$
- Recall that the socially-optimal outcome solves $C'_M\left(y_M^{\star}\right) + D'\left(y_M^{\star}\right) = p_M$, so

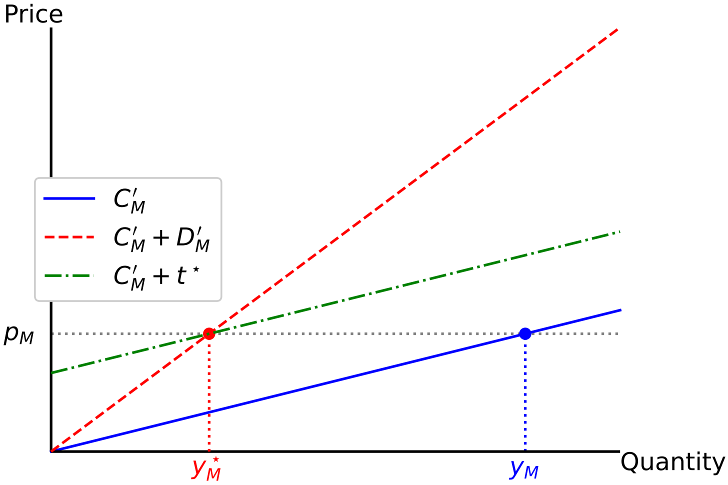
$$C'_M\left(y_M^{tax}\right) = C'_M\left(y_M^{\star}\right)$$

- Since we assumed that marginal costs are strictly increasing, it must be that

$$y_M^{tax} = y_M^{\star}$$

  - I.e. the private choice equals the social choice

Example: $C_M(y) = 0.5y^2$ and $D(y) = y^2$



Roadmap

1. Elements of Economic Models
2. Production Externality
3. Pigouvian Taxes
4. Command and Control Regulation
5. The Coasian Insight
6. Regulation in space

Command and control regulation

- A central authority could
  - command that Producer M must cut its supply from y_M to y_M^* and
  - control that this target is complied by Producer M
- Command and control regulation does not operate based on the price mechanism
- In our example, the optimal command and control regulation and the optimal Pigouvian tax deliver the same outcome
- In general, that need not be the case (more details in e.g. pp. 159-162 of Tol, 2022)
  - Price and quantity instruments respond differently to lobbying or mistakes by the regulator
  - Weitzman (1974) argued that which is preferred depends on "relative slope" of marginal cost to marginal benefits of abatement

Roadmap

1. Elements of Economic Models
2. Production Externality
3. Pigouvian Taxes
4. Command and Control Regulation
5. The Coasian Insight
6. Regulation in space

The Coasian insight

- Let us step back and ask: **Does market never internalize the externalities?**
- In an influential paper, "The Problem of Social Cost", Coase revisited this question
- Coase argues that under certain conditions, self-interested parties will bargain to achieve an efficient outcome
- Key to this discussion is that there are well-defined **property rights**
    1. In one extreme, Producer A has all the rights to avoid all the damages from pollution
    2. In another extreme, Producer M has all the rights to pollute

Case #1: Producer A has all the rights to avoid pollution

- Since any level of production of good M means some pollution, the initial point for Producer M and Producer A to negotiate is where production of good M is zero, $y_M = 0$
- Let us consider how the two parties may bargain:
  - Producer A will ask to be compensated at least for the damage that Producer M generates
  - Producer M will accept to pay any amount to Producer A provided that the agreed pollution that it generates still corresponds to a positive profit for M
- If Producer A's minimum willingness to receive compensation is less than Producer M's maximum willingness to pay, then the two parties can make a contract in which Producer M produces at the efficient level of $q_M^\star$

Case #2: Producer M has all the rights to pollute

- In this case, the starting point is where Producer M maximizes its profit in an unrestricted manner
- Again, let us consider how the two parties may bargain:
  - Producer M will ask to be compensated at least for the loss in its (marginal) profit
  - Producer A will accept to pay any amount to Producer 1 if that is no greater than the (marginal) damage it incurs
- If Producer M's minimum willingness to receive compensation is less than Producer A's maximum willingness to pay, then the two parties can make a contract in which Producer M produces at the efficient level of $q_M^\star$

The Coase Theorem

- Therefore, the efficient outcome can be achieved between the two self-interested parties
  - Regardless of the initial distribution of property rights
- Coase himself did not expressed his insight into a formal theorem, it was subsequently put into the "Coase Theorem:"
  Suppose property rights are well-defined, enforceable at no costs, and transferable via contracts with sufficiently small transaction costs. Then, agents will bargain with each other to reach an efficient outcome regardless of how property rights are initially assigned

Takeaways from the Coase Theorem

1. The statement that markets fail to internalize externalities relies on implicit presumptions
   - After all, markets do not exist in vacuum. They function in the context of institutions that allocate and enforce property rights
   - Moreover, a market failure can be partly a consequence of non-existing markets for transferring property rights (e.g., the right to pollute, or the right to be immune from pollution)
2. The Theorem can be interpreted as to why externalities are not dealt with via market mechanisms:
   - When property rights are not well-defined and institutions to enforce contracts too weak, ...
   - ... and, when costs of gathering and communicating information that makes transactions (of rights) possible are too large

Roadmap

1. Elements of Economic Models
2. Production Externality
3. Pigouvian Taxes
4. Command and Control Regulation
5. The Coasian Insight
6. Regulation in space

What about space?

- Our pollution regulation model has so far no role for space
- Two ways in which space matters
  - The spatial scope of policy (regional social planners)
  - The impact of regulation on firm locations

Production externalities with 2 regions: model setup

- We will now have two regions, $i = 1$ and $i = 2$
- In region $i = 1$ there is a M producer and an A producer with profits

$$\begin{aligned}\pi_{1,M} &= p_M y_M - C_M\left(y_{1,M}\right) \\ \pi_{1,A} &= p_A y_{1,A} - C_A\left(y_{1,A}\right) - D\left(y_{1,M}\right)\end{aligned}$$

- In region $i = 2$ there is only an A producer with profits

$$\pi_{2,A} = p_A y_{2,A} - C_A\left(y_{2,A}\right) - D\left(y_{1,M}\right)$$

- Function $D\left(y_{1,M}\right)$ measures the pollution **damages**
  - Generated by the manufacturer in region 1
  - Suffered by the agricultural firms in both regions

Unregulated market and socially-optimal outcomes

- The unregulated private choices $y_{1,M}$, $y_{1,A}$ and $y_{2,A}$ are determined by

$$C'_M\left(y_{1,M}\right) = p_M \text{ and } C'_A\left(y_{i,A}\right) = p_A \text{ for } i \in \{1,2\}$$

- The socially-optimal outputs $y^\star_{1,M}$, $y^\star_{1,A}$ and $y^\star_{2,A}$ maximize joint profits across regions:

$$\pi_{1,M}\left(y^\star_{1,M}\right) + \sum_{i=1}^{2} \pi_{i,A}\left(y^\star_{i,A}, y^\star_{1,M}\right)$$

and the first order conditions for M is

$$C'_M\left(y^\star_{1,M}\right) + D'\left(y^\star_{1,M}\right) + D'\left(y^\star_{1,M}\right) = p_M$$

and those for A are $C'_A\left(y^\star_{i,A}\right) = p_A$ for $i \in \{1,2\}$

Optimal Pigouvian tax

- The optimal Pigouvian tax is thus

$$t^\star = 2D'\left(y^\star_{1,M}\right)$$

- The choice of output by M facing tax t, $y^{tax}_{1,M}$, solves

$$C'_M\left(y^{tax}_{1,M}\right) + t = p_M$$

- With the same steps explained before, one can show that if $t = t^\star$ then

$$y^{tax}_{1,M} = y^\star_{1,M}$$

  - i.e. the optimal Pigouvian tax implements the social optimum

Regional Pigouvian tax

- We now consider a planner that only has jurisdiction in Region 1
- Their objective is to maximize profits in their jurisdiction:

$$\pi_{1,M}\left(\tilde{y}_{1,M}\right) + \pi_{1,A}\left(\tilde{y}_{1,A}, \tilde{y}_{1,M}\right)$$

  - where $\tilde{y}_{1,M}$ and $\tilde{y}_{1,A}$ are region 1 socially-optimal production
- The first order condition for good M is

$$C'_M\left(\tilde{y}_{1,M}\right) + D'\left(\tilde{y}_{1,M}\right) = p_M$$

- The regional Pigouvian tax that implements $\tilde{y}_{1,M}$ is

$$\tilde{t}_1 = D'\left(\tilde{y}_{1,M}\right)$$

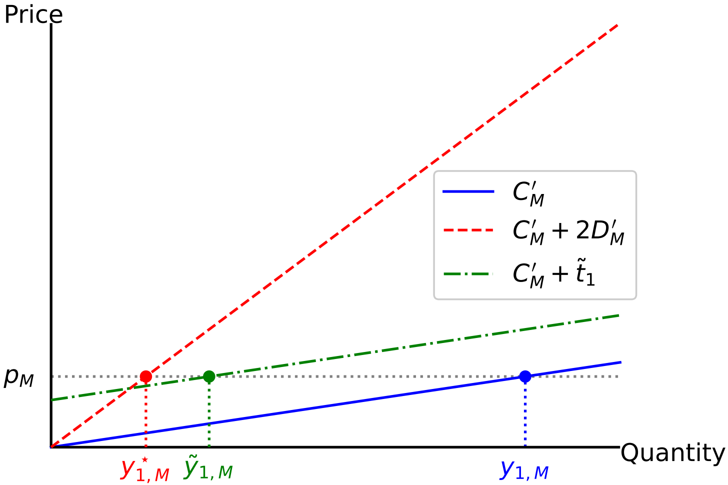
Example: $C_M(y) = 0.5y^2$ and $D(y) = y^2$

- Market outcome with tax t: $C'_M\left(y^{tax}_{1,M}\right) + t = p_M \iff y^{tax}_{1,M} = p_M - t$
- If $t = 0$: $y_{1,M} = p_M$
- If $t = t^\star = 2D'(\tilde{y}_{1,M})$: $y^\star_{1,M} = p_M - 4y^\star_{1,M} \iff y^\star_{1,M} = \frac{p_M}{5}$
- If $t = \tilde{t}_1 = D'(\tilde{y}_{1,M})$: $\tilde{y}_{1,M} = p_M - 2\tilde{y}_{1,M} \iff \tilde{y}_{1,M} = \frac{p_M}{3}$
- Therefore:

$$y^\star_{1,M} < \tilde{y}_{1,M} < y_{1,M}$$

  - The regional Piguvian tax is too low
  - Pollution regulation becomes less effective when the regulated area is not aligned with the structure of the externality

Example: $C_M(y) = 0.5y^2$ and $D(y) = y^2$



Firm location

- Our 2-region model assumes that firm locations are fixed
- But what if, after seeing the taxes and before producing, M could move?
- Producer M would choose the location that delivers highest profits
    - Profits with tax $t = \tilde{t}_1$ in region 1: $\tilde{\pi}_{1,M}$
    - Profits with tax $t = 0$ in region 2: $\pi_{2,M}$
- If production costs C_M and price p_M same in both regions, then producer M would move
- M production in region 1 will be 0 and in region 2 it will be the same as in the unregulated market
    - Polluting activity just shifted to the unregulated region!
    - An example of **leakage**

Example: $C_M(y) = 0.5y^2$ and $D(y) = y^2$

- Profits with tax $t = \tilde{t}_1$ in region 1:

$$\tilde{\pi}_{1,M} = p_M \tilde{y}_{1,M} - 0.5\left(\tilde{y}_{1,M}\right)^2 - 2\tilde{y}_{1,M}\tilde{y}_{1,M} = \frac{1}{18}\left(p_M\right)^2$$

  with $\tilde{y}_{1,M} = \frac{p_M}{3}$

- Profits with tax $t = 0$ in region 2:

$$\pi_{2,M} = p_M y_{2,M} - 0.5\left(y_{2,M}\right)^2 = \frac{1}{2}\left(p_M\right)^2$$

  with $y_{2,M} = p_M$

- Since $\pi_{2,M} > \tilde{\pi}_{1,M}$ the firm will produce in region 2
  - And the total produced is p_M, same as in the unregulated market

Appendix

References I

Farrokhi, F. (2022): *Environmental Economics: Lecture Notes*: MS Columbia University, https://www.faridfarrokhi.com/teaching/environmental-econ-msc.

Tol, R. S. (2022): *Environmental Economics: Lecture notes*: Tol Tales Publishing, https://buymeacoffee.com/richardtol/e/338460.

Weitzman, M. L. (1974): "Prices vs. Quantities," *The Review of Economic Studies*, 41, 477–491, 10.2307/2296698.