

Environmental Economics and Climate Change

Professor: Bård Harstad

University of Oslo

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- micro
- game theory
- public economics
- political economics
- development economics
- behavioral economics
- international trade
- macro

Environmental Problems

- Overusing/exploiting renewable and exhaustible resources
 - Atlantic northwest cod fishery has collapsed before... (1992).
- Land use changes (e.g. tropical deforestation)
 - football pitch cleared from the Amazon rainforest every minute.
- Waste (e.g. hazardous, or plastic)
 - 40 percent of plastic is used only once. An estimated five trillion pieces of plastic floating on and in the world's oceans.
- Water (over-usage, or contamination)
 - 9 percent of the world's population don't have access to safe drinking water. 40 percent of the world's population don't have proper sanitation (WHO).
- Air (particles, NO_x , acid rain; ozone layer)
 - Reduce life expectancy by 1y (LA), 4y (China), 9y (India).
- Greenhouse gases (e.g., CO_2)
 - UN goal: 2 (1,5) $^{\circ}\text{C}$, but "93 per cent chance that global warming will exceed 4C by the end of this century".

Classifications

- National vs. international
- Political vs. market-based
- Number of sources and number of affected parties
- Affecting producers vs consumers
- Tangible vs. nonverifiable pollutants
- Flow pollutants vs. accumulating stocks
- Contemporary vs. long-term effects

- ① Welfare theorems and market failures (Pigou)
- ② Policy instruments (Coase and Weitzman)
- ③ Emissions and technology in repeated games
- ④ Architectures for agreements (dynamic games)
- ⑤ Free-riding vs. participation
- ⑥ TBA: You are invited to vote over the following alternative topics:
 - Political economy of instruments and treaties
 - Coal, oil, and supply-side environmental policy
 - Deforestation in the tropics and conservation
 - Discounting and the value of the future

Outline

- ① Welfare theorems and market failures (Pigou) (micro)
- ② Policy instruments (Coase and Weitzman) (public ec.)
- ③ Emissions and technology in repeated games
- ④ Architectures for agreements (dynamic game theory)
- ⑤ Free-riding vs. participation (contract theory)
- ⑥ TBA: You are invited to vote over the following alternative topics:
 - Political economy of instruments and treaties (political economy)
 - Coal, oil, and supply-side environmental policy (resource ec.)
 - Deforestation in the tropics and conservation (development ec.)
 - Discounting and the value of the future (behavioral ec.)

Consumption and Production: "ECON 101"

- Consumers i 's utility and good j 's production function:

$$u^i(x_1^i, \dots, x_J^i) \text{ and } \sum_i x_j^i \leq f^j(y_j^1, \dots, y_j^K),$$

- ...where $i \in \{1, \dots, I\}$ consumes x_j^i of good $j \in \{1, \dots, J\}$, and y_j^k is the quantity of input $k \in \{1, \dots, K\}$ used in the production of good j .
- Pareto optimality (PO)** requires that

$$\begin{aligned} & \max_{\{x_j^i\}, \{y_j^k\}} u^1(x_1^1, \dots, x_J^1) \text{ s.t.} \\ u^i(x_1^i, \dots, x_J^i) & \geq \bar{u}^i, \forall i && (\text{shadow value: } \lambda_i), \\ \sum_i x_j^i & \leq f^j(y_j^1, \dots, y_j^K) \quad \forall j && (\text{shadow value: } \mu_j), \\ \sum_j y_j^k & \leq \bar{y}^k \quad \forall k && (\text{shadow value: } \eta_k). \end{aligned}$$

for some default levels ($\bar{u}^i$'s) and input quantities ($\bar{y}^k$'s).

- Do we need to include labor/leisure in the model?*

Consumption and Production: Pareto Optimality

- Lagrange (/Kuhn-Tucker) problem with foc for x_j^i and y_j^k (if $\lambda_1 \equiv 1$):

$$\lambda_i u_j^i = \mu_j,$$

$$\mu_j f_k^j = \eta_k.$$

- The shadow values depend on the default levels; the $\bar{u}_i$'s.
- For PO, it is sufficient that the foc's hold for *some* shadow values.
- When the foc's are combined:

$$\frac{u_j^i}{u_{j'}^i} = \frac{\mu_j}{\mu_{j'}} = \frac{u_k^{i'}}{u_l^{i'}} \quad \forall (i, i'), (j, j') \quad (\text{efficiency in consumption}),$$

$$\frac{f_k^j}{f_{k'}^j} = \frac{\eta_k}{\eta_{k'}} = \frac{f_k^{j'}}{f_{k'}^{j'}} \quad \forall (k, k'), (j, j') \quad (\text{efficiency in production}),$$

$$\frac{u_j^i}{u_{j'}^i} = \frac{f_k^{j'}}{f_k^j} \quad \forall (j, j'), i, k \quad (\text{efficiency in exchange}).$$

Consumption and Production: Market Equilibrium

- Consumers' choice, given endowment E^i (with shadow value v_i):

$$\max_{\{x_j^i\}_j} u^i(x_1^i, \dots, x_J^i) \text{ s.t. } \sum_j p_j x_j^i \leq E^i(v_i) \Rightarrow u_j^i = v_i p_j.$$

- Producers:

$$\max p_j f^j(y_j^1, \dots, y_j^K) - \sum_k w^k y_j^k \Rightarrow p_j f_k^j = w^k.$$

- Combined:

$$\begin{aligned} \frac{u_j^i}{u_{j'}^i} &= \frac{\mu_j}{\mu_{j'}} = \frac{u_j^{i'}}{u_{j'}^{i'}} \text{ if just } \mu_j = p_j, \\ \frac{f_k^j}{f_{k'}^j} &= \frac{\eta_k}{\eta_{k'}} = \frac{f_k^{j'}}{f_{k'}^{j'}} \text{ if just } \eta_k = w^k, \\ \frac{u_j^i}{u_{j'}^i} &= \frac{f_k^{j'}}{f_k^j} = \frac{p_j}{p_{j'}} \quad \forall (j, j'), i, k. \end{aligned}$$

Theorem

- ① *Every market equilibrium $\Rightarrow$ Pareto optimal.*
 - ② *Every Pareto optimal outcome $\Rightarrow$ market equilibrium – given some allocation of endowments.*
- Where is the environment?

Consumption and Production: With Externalities

- Externalities from inputs/productions to consumers:

$$u^i \left(x_1^i, \dots, x_J^i, \sum_j g_j \right) \text{ and } \sum_i x_j^i \leq f^j \left(y_j^1, \dots, y_j^K, g_j \right).$$

- Pareto Optimality is given by the same conditions as above, plus:

$$\mu_j f_g^j = \sum_i \lambda_i (-u_g^i) = \sum_i \frac{\mu_j}{u_j^i} (-u_g^i) \Rightarrow f_g^j = \sum_i \frac{-u_g^i}{u_j^i}.$$

- Market equilibrium with no regulation: j emits until $f_g^j = 0$.
- With regulation or tax t_g^j on j 's emission: $p_j f_g^j = t_g^j$
- This coincides with the PO outcome if

$$f_g^j = \frac{t_g^j}{p_j} = \sum_i \frac{-u_g^i}{u_j^i} = \sum_i \frac{-u_g^i}{p_j u_1^i / p_1} \Rightarrow t_g^j = \sum_i \frac{-u_g^i}{u_1^i} p_1.$$

- So, the emission **tax should be the same for all firms**, no matter how valuable/dirty they are.

Consumption and Production: With Externalities (cont.)

- If there is a numeraire good (i.e., $u_1^i = 1 = p_1$), then $t_g^j = -\sum_i u_g^i$.
- Alternatively, the regulator may decide on the g_j 's directly.
- For each such policy, there will be equilibrium prices and quantities such that payoffs are functions $u_i(\mathbf{g})$ and profits $\pi_j(\mathbf{g})$.
- Larger g_j 's is likely to benefit producer j ($B_j(g_j)$) but be costly for consumers ($C_i(g_j)$).

Externalities and Public Goods

- Let g_i be emission by agent $i \in N \equiv \{1, \dots, n\}$, and $\mathbf{g} = \{g_1, \dots, g_n\}$.
- **Externalities:**

$$u_i(\mathbf{g}) = B_i(g_i) - C_i(\mathbf{g}), \text{ if } \partial C_i / \partial g_j \neq 0 \text{ for some } j \neq i.$$

- **Uniformly mixing pollutant (and public good/bad):**

$$u_i(\mathbf{g}) = u_i(g_i, G) = B_i(g_i) - C_i(G), \text{ where } G = \sum_{j \in N} g_j.$$

- To get a unique solution, assume u_i is concave in g_i
 - For example: Every B_i is concave while C_i is convex.
- **Business as usual** (interior) equilibrium:

$$B'_i(g_i) = C'_i(G).$$

- Suppose transfers enter linearly and additively in u_i .
- **The first-best** (FB; the unique PO outcome with transfers):

$$B'_i(g_i^*) = \sum_{j \in N} C'_j(G^*).$$

Pigou Taxes (The "Incorrect Prices" Approach)

- Suppose i pays $t_i g_i$ and receives $T_i(\mathbf{g})$.
- Then, in equilibrium:

$$\frac{\partial B_i(g_i)}{\partial g_i} = C'_i(G) + t_i - \frac{\partial T_i(\mathbf{g})}{\partial g_i}.$$

- Equivalent: A *subsidy* $T_i(\mathbf{g}) - t_i g_i$, f.ex. $t_i \cdot (\bar{g}_i - g_i)$.
- This coincides with the first-best if:

$$t_i = \sum_{j \in N \setminus i} C'_j(G) \text{ and } \frac{\partial T_i(\mathbf{g})}{\partial g_i} = 0.$$

- *No earmarking*: It is (almost) irrelevant how tax revenues are spent.
 - For example: $T_i(\mathbf{g}) = \sum_{j \in N \setminus i} t_j g_j / (n - 1)$.
- If $C'_j \approx 0$ for each emitter, the linear tax is the same for all:

$$t = \sum_{j \in N} C'_j(G^*) \Rightarrow B'_i(g_i) = \sum_{j \in N} C'_j(G^*).$$

Pigou Taxes - Uncertainty

- Facing the same tax, we get:

$$B'_i(g_i, \epsilon_i) = t = B'_j(g_j, \epsilon_j) \forall (i, j) \in N^2$$

even if individual shocks (ϵ_i) are **private information**.

- Then, define $\epsilon = (\epsilon_1, \dots, \epsilon_n)$ and

$$B(t, \epsilon) \equiv \sum_{i \in N} B_i(B_i'^{-1}(t, \epsilon_i), \epsilon_i).$$

- The optimal tax is given by:

$$\max_t E \left[B(t, \epsilon) - C \left(\sum_{i \in N} B_i'^{-1}(t, \epsilon_i) \right) \right].$$

Pigou Taxes - Uncertainty - Example Q

- Consider the **quadratic approximation** ($Y = \text{exp. "bliss" point}$):

$$B(G, \epsilon) = -\frac{b}{2} (Y - G - \epsilon)^2 \text{ and } C(G) = \frac{c}{2} G^2,$$

where the aggregate **shock** is $\epsilon \in \mathbb{R}$, $E\epsilon = 0$, and **variance** $E\epsilon^2 = \sigma_\epsilon^2$.

- The equilibrium, given t :

$$\max_G -\frac{b}{2} (Y - G - \epsilon)^2 - tG \Rightarrow b(Y - G - \epsilon) = t.$$

- The tax pins down B' and B , leaving the uncertainty to G and $C(G)$.
- The optimal t :

$$\max_t -\frac{t^2}{2b} - E \frac{c}{2} (Y - \epsilon - t/b)^2 \Rightarrow t^* = c(Y - t^*/b) = \frac{cbY}{b+c}.$$

- The uncertainty does not influence the optimal level of t . (Why?)
- Welfare loss** relative to no uncertainty increases in c :

$$L_t^\epsilon = \frac{c\sigma_\epsilon^2}{2}.$$

Pigou Taxes and Tax Revenues

- Tax revenues (at the above optimal t^*):

$$EtG = E \frac{cbY}{b+c} \left(Y - \epsilon - \frac{cY}{b+c} \right) = \frac{cb^2 Y^2}{b+c}.$$

- Tax revenues (at general t):

$$t(Y - \epsilon - t/b)$$

- Normally, revenues necessitate distortionary taxes.
- With the social value λ , the optimal t is thus:

$$\begin{aligned} \max_t -\frac{t^2}{2b} - E \frac{c}{2} (Y - \epsilon - t/b)^2 + E \lambda t (Y - \epsilon - t/b) &\Rightarrow \\ t = c(Y - t/b) + \lambda b(Y - 2t/b) &= \frac{cb + \lambda b^2}{b + c + 2\lambda b} Y. \end{aligned}$$

- which can be increasing or decreasing in λ ...
- Q: (When) is there a "double dividend"?

Proposition

- ① *Weak form: The regulation with Pigou tax revenues raises social efficiency relatively to regulation without tax revenues.*
 - *Holds trivially*
- ② *Strong form: The optimal tax is larger than the Pigovian level.*
 - *The strong form may or may not hold.*

Emission Trading Systems (ETS): A Brief History

- Theory by Coase '60, Crocker '66, Dales '68, Montgomery '72
- Computer simulates late 60s by the EPA
- 1977 Clean Air Act: Permitted "offset-mechanism"
- 1990 Clean Air Act: Cap-and-trade in (SO₂)
 - cost savings of \$700–\$800m/year compared to uniform emission rate standard (Carlson et al. '00 JPE)
 - SO₂ emissions were reduced by 50% from 1980 levels by 2007
- 1997: Kyoto: CDM and JI
- 2005: EU ETS: First and largest CO₂ ETS
- RGGI, WCI, China (2020?)
- Linkages considered, but no global system

Coase (The "Property Rights" Approach)

- Suppose disagreement leads to the "default" payoffs u_i^D . For example, u_i^D may equal $u_i(\mathbf{g}^{BAU})$.
- To negotiate a better outcome, a "proposer", i , would prefer to:

$$\max_{\mathbf{g}, \mathbf{t}} u_i = B_i(g_i) - C_i(G) - t_i \text{ s.t.}$$

$$u_j = B_j(g_j) - C_j(G) - t_j \geq u_j^D \text{ (IR}_j\text{)}.$$

- With budget balance, $t_i = -\sum_{j \in N \setminus i} t_j$, so i prefers the largest t_j 's satisfying IR_j.
- IR_j can be substituted into u_i , so that i maximizes:

$$\begin{aligned} \max_{\mathbf{g}, \mathbf{t}} u_i &= B_i(g_i) - C_i(G) + \sum_{j \in N \setminus i} [B_j(g_j) - C_j(G) - u_j^D] \\ &= \sum_{j \in N} [B_j(g_j) - C_j(G)] - \sum_{j \in N \setminus i} u_j^D = \sum_{j \in N} u_j(\mathbf{g}^*) - \sum_{j \in N \setminus i} u_j^D. \end{aligned}$$

- In other words: i maximizes the **sum of payoffs** (minus a constant).
- Consequently, the proposed g_j 's coincides with the **first best**.

Coase Theorem (1960)

Theorem

- *The parties negotiate the efficient outcome, regardless of the initial allocation of property rights (i.e., the default outcome, u_j^D) as long as there are no 'transaction costs.'*
- For example, u_j^D may reflect BAU (i.e., everyone has the "right" to emit as much as they want), or u_j^D could be $u_j(\mathbf{0})$, i.e., no-one has the right to emit anything.
- "Transaction costs" (tc_i) must be sufficiently small:

$$tc_i \leq \sum_{j \in N} \left[u_j(\mathbf{g}^*) - u_j^D \right].$$

- Q: What is this "transaction cost"?
- Q: Who should have the bargaining power? What should the property rights be, if there are substantial transaction costs?

Trading Pollution Permits ("Missing Market")

- If i has the right to emit Q_i^0 , while j has the right to emit Q_j^0 , the two might benefit from trading without increasing total emission:

$$g_i + g_j \leq Q_i^0 + Q_j^0.$$

- That is, if i emits g_i and sell $Q_i^0 - g_i$, j can emit g_j from buying $g_j - Q_j^0 = Q_i^0 - g_i$ from i .
- This trade is beneficial as long as $B'_i < B'_j$.
- With efficient trade, $B'_i = B'_j$.
- More generally, a proposer i prefers to:

$$\max_{\mathbf{g}, \mathbf{t}} u_i = B_i(g_i) - C_i(G) - t_i \text{ s.t.}$$

$$u_j = B_j(g_j) - C_j(G) - t_j \geq u_j^D \text{ (IR}_j\text{) and}$$

$$G = \sum_{j \in N} g_j \leq \sum_{j \in N} Q_j^0 \text{ and } \sum_{j \in N} t_j \geq 0.$$

- Consequently, $B'_i = B'_j$ for all pairs (i, j)
- ...regardless of the endowments, i.e., u_j^D .

Perfect Pollution Markets ("Missing Market")

- If $n \rightarrow \infty$, every i is likely to take the permit price p as given.
- If i owns Q_i^0 permits already, i solves

$$\max_{g_i} B_i(g_i) - C_i(G) - p(g_i - Q_i^0) \Rightarrow B'_i(g_i) = p,$$

since $G = \sum_{j \in N} Q_j^0$ is independent of g_i .

- The outcome is FB if:

$$p = \sum_{j \in N} C'_j(G^*).$$

- I.e., the outcome is FB if the quantity (and thus the price) is "right", i.e., if:

$$B_i(g_i) = p = \sum_{j \in N} C'_j(G^*).$$

Perfect Pollution Markets ("Missing Market")

Proposition

- *When each emitter is a price-taker, the permit market equilibrium is efficient, regardless of the initial allocation of rights.*
- So, permit trade $\Rightarrow$ FB whether n is small or $n = \infty$.
 - Should we expect FB for any n ? Why/why not?
- Q: Why is the initial allocation (Q_i^0) irrelevant?
- Q: Is that useful for the regulator? How will the regulator decide on the initial endowments? Must Q_i^0 be exogenous?
- What if Q_i^0 depends on past production or past emissions?
- **Montgomery '72**: With $G_j = \sum_{i \in N} h_{ij} g_i$, the FB requires:

$$B'_i(g_i) = \sum_{j \in N} h_{ij} C'_j(G_j^*) \Rightarrow \text{Pollution markets FB iff } p_j = C'_j.$$

Perfect Pollution Markets - Uncertainty

- Private information: Conditions above (when $n = \infty$) hold if the benefit is $B_i(g_i, \epsilon_i)$, where ϵ_i is i 's private information.
- Total benefit in equilibrium is:

$$B(G, \epsilon) = \max_{\mathbf{g}} \sum_{j \in N} B_j(g_j, \epsilon_j) \text{ s.t. } \sum_{j \in N} g_j = G.$$

- The optimal cap is

$$\max_G EB(G, \epsilon) - C(G) \Rightarrow EB'(G, \epsilon) = C'(G).$$

- Example Q (with a single aggregate shock $\epsilon \in \mathbb{R}$):

$$Eb(Y - G + \epsilon) = cG \Rightarrow G^* = \frac{b}{c + b} Y.$$

- The shock does not affect G , but only B' .
- Relative to no uncertainty, the welfare loss is:

$$L_G^\epsilon = \frac{b\sigma_\epsilon^2}{2}.$$

Prices vs. Quantities (Weitzman '74)

Proposition

- *The efficiency loss under quotas is smaller than under prices/taxes, $L_G^\epsilon < L_t^\epsilon$, IFF $b < c$.*
- This holds generally when B and C are approximated by quadratic functions, no matter the distribution of errors, and even if there are (additive) shocks in the C function (Q: Why?)
- Rather than comparing welfare to the situation without uncertainty, we can compare to the first-best outcome with the shock. (Q: Why?)
- Q: Without shocks in $B(\cdot)$, a shock in $C(\cdot)$ is irrelevant for the comparison, and then the slopes are also irrelevant. (Why?)
- Q: How can the losses be reduced further?
- By hybrid schemes?
- Floor/ceiling for price?

Prices vs. Quantities: Revenues

- Pigou taxes raises revenues, which has an additional benefit.
- The willingness to pay for a quota is B' , so the revenues when auctioning the initial quota endowments are:

$$\frac{b}{c+b} Y b \left(Y - \frac{b}{c+b} Y + \epsilon \right) = \frac{b^2 Y}{c+b} \left(\frac{c}{c+b} Y + \epsilon \right).$$

- This has the same mean as the expected Pigou tax revenues.
- The variance of the auction revenues is smaller IFF $b < c$.
- This adds to the benefits of quotas, rather than taxes, IFF $b < c$.