

Dynamic Games in Environmental Economics: Compliance and Self-enforcing Agreements

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Outline

Motivation and concepts

1. Repeated prisoner dilemmas and technology
2. Returning to our workhorse model
3. A "quantity" agreement.
4. A "price" agreement"

Extensions and further readings

Motivation - Paris 2015

- Climate is "the ultimate public good"
 - There is no world government
 - There is no explicit sanctions
 - International agreements must be self-enforcing
- One thing is whether to participate, recognizing that then one gets, at least, some influence.
- But after the promises are made, and the others are about to comply to the promises, it seems more tempting to defect than to free ride in the first place.
 - Compliance is the main problem
- Focus on transparency: The climate agreement calls for the U.N. Framework Convention on Climate Change to publish all national action plans on its Web site and for scientists to calculate the contributions these plans make to curbing emissions.
- A Climate Accord Based on "Global Peer Pressure" (NYT)

Important Concepts and Equilibria Refinements

Normal form game	Nash equilibrium
Extensive form game	Subgame-perfect equilibrium
Stochastic game	Markov-perfect equilibrium

1. The Prisoner Dilemma Game

- Abatements are costly but benefit others
- The prisoner dilemma (PD) game is a reasonable starting point.
- Let g_i be the emission of $i \in \{1, \dots, n\}$, $B(g_i)$ the benefit of polluting, C the marginal cost of greenhouse gases:

$$u_i = B(g_i) - C \sum_{i=1}^n g_i.$$

- If $g \in \{\underline{g}, \bar{g}\}$, the first-best agreement is simply $g = \underline{g}$ if:

$$B(\bar{g}) - B(\underline{g}) < (\bar{g} - \underline{g}) Cn.$$

- But polluting more is a dominant strategy if:

$$B(\bar{g}) - B(\underline{g}) > (\bar{g} - \underline{g}) C.$$

- The emission game is a prisoner dilemma game if both holds:

$$1 < \frac{B(\bar{g}) - B(\underline{g})}{C(\bar{g} - \underline{g})} < n.$$

1. The Repeated Prisoner Dilemma Game

- *Fudenberg and Maskin '86*: **Folk theorem** with Nash equilibrium and SPE: Every $v \in \mathcal{F}$ is possible if $v_i \geq \underline{v}_i \equiv \min \max v_i$ for δ large.
- In PD, the "minmax" strategy is simply $g = \bar{g}$.
- With (grim) trigger strategies, cooperation ($g = \underline{g}$) is an SPE if

$$\begin{aligned} \frac{B(\underline{g}) - Cn\underline{g}}{1 - \delta} &\geq B(\bar{g}) - C\bar{g} - C(n-1)\underline{g} + \delta \frac{B(\bar{g}) - Cn\bar{g}}{1 - \delta} \Leftrightarrow \\ B(\bar{g}) - B(\underline{g}) &\leq C(\bar{g} - \underline{g})[\delta n + (1 - \delta)] \end{aligned}$$

- So, as long as the first best requires $g = \underline{g}$, cooperation is possible for sufficiently high discount factors:

$$\delta \geq \hat{\delta} \equiv \frac{1}{n-1} \left[\frac{B(\bar{g}) - B(\underline{g})}{C(\bar{g} - \underline{g})} - 1 \right] < 1.$$

- If $\delta < \hat{\delta}$, the unique SPE is $g = \bar{g}$.

1. Emissions and Technology

- Consider next a stage game with both emissions and technology investments $(r_{i,t})$:

$$u_{i,t} = B(g_{i,t}, r_{i,t}) - C(r_{i,t}) \sum_{i=1}^n g_{i,t} - kr_{i,t}.$$

- $B(\cdot)$ is increasing and concave in both arguments. Examples:
 - "green" technologies: $B_{gr} < 0$ and $C_r = 0$
 - "brown" technologies: $B_{gr} > 0$ and $C_r = 0$
 - "adaptation" technologies: $B_{gr} = 0$ and $C_r < 0$
- With binary g , we can define

$$B_{gr} \equiv \frac{B_r(\bar{g}, \hat{r}) - B_r(\underline{g}, \hat{r})}{\bar{g} - \underline{g}}.$$

- Linear investment-cost k is here a normalization. (Q: Why?)
- Will be added below: Heterogeneity, spillovers, continuous g , and uncertainty.

1. Benchmarks

- The first-best outcome is $g = \underline{g}$ and

$$B_r(g, r^*) - ngC_r(r^*) = k.$$

- The business-as-usual outcome is $g = \bar{g}$ and

$$B_r(g, r^b) - ngC_r(r^b) = k.$$

- Given g , every country will voluntarily invest optimally in r .
- Once g has been committed to, there is no need to negotiate r .
- With such commitments, the first-best agreement is simply $g = \underline{g}$.

1. Problem: Motivating Compliance

- The compliance constraint above becomes:

$$\delta \geq \hat{\delta}(r) \equiv \frac{1}{n-1} \left[\frac{B(\bar{g}, r) - B(\underline{g}, r)}{C(r)(\bar{g} - \underline{g})} - 1 \right] < 1.$$

- Now, the temptation to defect depends on the technology.
- Thus, δ is a function of the technology.
- How can technology motivate compliance?

1. Problem: Deriving the best SPE

- The maximization problem is:

$$\max_{r, \underline{g} \in \{\underline{g}, \bar{g}\}} \frac{B(\underline{g}, r) - n\underline{g}C(r) - kr}{1 - \delta}$$

- subject to the two "compliance constraints" (CC^r) and (CC^g):

$$\frac{B(\underline{g}, r) - n\underline{g}C(r) - kr}{1 - \delta} \geq B(g^b(\tilde{r}), \tilde{r}) - [g^b(\tilde{r}) + (n-1)g^b(r)]C(\tilde{r}) - k\tilde{r} + \frac{\delta u^b}{1 - \delta} \quad \forall \tilde{r},$$

$$\frac{B(\underline{g}, r) - n\underline{g}C(r) - \delta kr}{1 - \delta} \geq B(\bar{g}, r) - [\bar{g} + (n-1)\underline{g}]C(r) + \frac{\delta u^b}{1 - \delta}.$$

- Folk theorem:** There exists $\hat{\delta}^r < 1$ and $\hat{\delta}^g < 1$ such that the first-best can be sustained as an SPE iff $\delta \geq \max\{\hat{\delta}^r, \hat{\delta}^g\}$.
- For climate policies, we might have $\delta < \max\{\hat{\delta}^r, \hat{\delta}^g\}$..

1. Compliance Constraints

Proposition

- CC^r never binds if an agreement is beneficial (i.e., $\hat{\delta}^r = 0$).

- CC^g can be written as:

$$B(\underline{g}, r) - n\underline{g}C - kr - (1/\delta - 1) [B(\bar{g}, r) - B(\underline{g}, r) - (\bar{g} - \underline{g}) C] \geq 0$$

- CC^g is more likely to hold for large δ , n , or $C(r)$.
- Maximizing lhs of CC^g wrt r gives the "most robust" compliance technology $\hat{r}$:

$$\begin{aligned} \frac{B_r(\underline{g}, \hat{r}) - n\underline{g}C_r(\hat{r}) - k}{1/\delta - 1} &= B_r(\bar{g}, \hat{r}) - B_r(\underline{g}, \hat{r}) - (\bar{g} - \underline{g}) C_r(\hat{r}) \\ &\approx (\bar{g} - \underline{g}) [B_{gr} - C_r] \Leftrightarrow \\ \hat{r} &> r^* \text{ IFF } B_{gr} - C_r < 0. \end{aligned}$$

1. Equilibrium Technology

Proposition

- Let $C(r) \equiv hf(r)$. For every r , we have $\hat{\delta}_h(r) < 0$ and $\hat{\delta}_n(r) < 0$.
- Suppose $\delta \leq \hat{\delta}^g \equiv \hat{\delta}(r^*)$. If h , n , or δ decreases, then
 - $r > r^* \uparrow$ for "green" technologies (where $B_{gr} < 0$ and $C_r = 0$)
 - $r < r^* \downarrow$ for "brown" technologies (where $B_{gr} > 0$ and $C_r = 0$)
 - $r < r^* \downarrow$ for "adaptation" technologies (where $B_{gr} = 0$ and $C_r < 0$)

1. Heterogeneity

Proposition

- CC^g only depends on individual parameters.
- Suppose $\delta_i \leq \hat{\delta}_i (r_i^*)$. If h_i , δ_i , n or i 's size decreases, then
 - $r_i < r_i^* \downarrow$ for "**adaptation**" technologies (where $B_{gr}=0$ and $C_r<0$)
 - $r_i < r_i^* \downarrow$ for "**brown**" technologies (where $B_{gr}>0$ and $C_r=0$)
 - $r_i > r_i^* \uparrow$ for "**green**" technologies (where $B_{gr}<0$ and $C_r=0$)
- Reluctant countries should do **more!** (i.e., invest more in green technologies and less in brown.)
- *True:* One problem is to persuade a reluctant country to *participate*.
- However, the harder problem is to ensure that they are willing to *comply* - once they expect others to comply.
- Reluctant countries should be helped to make such **self-commitment**, and this can be done with technology!

1. Multiple Technologies

- Suppose $\delta < \hat{\delta}^g$.
- **Green technologies** and **brown technologies** are strategic **complements**: The more countries invest in drilling technologies, the more they must invest in green technologies.
- **Green technologies** and **adaptation technologies** are strategic **complements**: The more countries adapt, the more they must invest in green technologies.
- **Brown technologies** and **adaptation technologies** are strategic **substitutes**: The more countries invest in brown technologies, the less they should adapt.

2. Continuous Emission Levels

- Return to the **homogenous** setting.
- If y_i is total consumption of energy, g_i comes from fossil fuel, while r_i comes from renewable energy sources.
- Let $B(g, r) = -\frac{b}{2} (\bar{y} - y_i)^2$, where $y_i = g_i + r_i$.
- So, back to **green** technology.
- Let the investment-cost be quadratic.

2. Continuous Emission Levels

- Remember that when

$$\tilde{u}_{i,t} = -\frac{b}{2} (\bar{y}_{i,t} - g_{i,t} - r_{i,t})^2 - \frac{k}{2} (r_{i,t}^2 - q_R r_{i,t-1}^2) - cG_t,$$

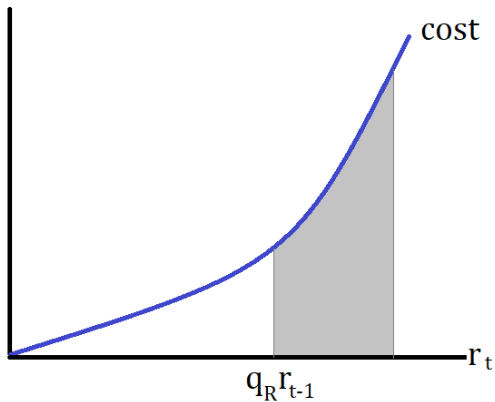
we can use

$$u_{i,t} = -\frac{b}{2} d_{i,t}^2 - \frac{k}{2} r_{i,t}^2 - C \sum_{j \in N} (\bar{y}_{j,t} - d_{j,t} - r_{j,t}), \text{ where}$$

$$d_{i,t} : = \bar{y}_{i,t} - g_{i,t} - r_{i,t},$$

$$C : = \frac{c}{1 - \delta q_G} \text{ and } k := (1 - \delta q_R) \frac{k}{2}.$$

2. Continuous Emission Levels



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- The Nash equilibrium/BAU ("b") of the stage game is:

$$bd_{i,t} = C \text{ and } kr_{i,t} = C = bd_{i,t}, \text{ so}$$

$$g^b = \bar{y} - \frac{C}{b} - \frac{C}{k} \text{ and } r^b = \frac{C}{k}.$$

- This gives the BAU payoff:

$$V^b = \frac{\frac{C^2}{b} \left(n - \frac{1}{2}\right) + \frac{C^2}{k} \left(n - \frac{1}{2}\right) - Cn\bar{y}}{1 - \delta}.$$

2. Continuous Emission Levels - First Best

- The socially optimal decisions are:

$$bd_{i,t} = b(\bar{y} - r_{i,t} - g_{i,t}) = Cn \Rightarrow g^*(r) = \bar{y} - r - \frac{Cn}{b},$$

$$kr_{i,t} = Cn = bd_{i,t} = b(\bar{y} - r_{i,t} - g_{i,t}) \Rightarrow r^*(g) = \frac{b(\bar{y} - g)}{k + b}.$$

- Combined, the **first-best** is

$$g^* = \bar{y} - \frac{Cn}{b} - \frac{Cn}{k} \text{ and } r^* = \frac{Cn}{k}.$$

3. Quantity Agreements - Compliance

- An equilibrium gives:

$$V^e = \frac{-\frac{b}{2}d^2 - \frac{k}{2}r^2 - Cn(\bar{y} - d - r)}{1 - \delta}.$$

- The best deviation at the emission stage is $d = C/b$, giving the CC^g :

$$\frac{b}{2} \left(d^2 - \frac{C^2}{b^2} \right) - C \left(d - \frac{C}{b} \right) \leq \delta (V^e - V^b).$$

- Let $\bar{\delta}^g$ be defined such that CC^g binds at the first best.
- The best deviation at the investment stage is $r = C/k$, giving CC^r :

$$C(n-1) \left(r - \frac{C}{k} \right) \leq V^e - V^b.$$

- Let $\bar{\delta}^r$ ensure that CC^r binds at the first best. By comparison, $\bar{\delta}^r < \bar{\delta}^g$ iff $k/b > 1/2$.
- Then, if $\delta \in (\bar{\delta}^r, \bar{\delta}^g)$, $g^e > g^*$ while $r^e = r^*$.
- Thus, $r^e > r^*(g^e)$, and countries over-invest conditional on g .

3. Quantity Agreements - Finding 1

- (i) The Pareto optimal SPE is first best when $\delta \geq \max \left\{ \bar{\delta}^g, \bar{\delta}^r \right\}$;
- (ii) If $k/b > 1/2$, then $\bar{\delta}^r < \bar{\delta}^g$ and, when $\delta \in \left[\hat{\delta}^r(g, r), \bar{\delta}^g \right)$, we have:

$$r = r^*(g^*) = r^*(g) + \frac{b}{b+k} \Lambda_q(\delta) \text{ and } g = g^* + \Lambda_q(\delta) > g^*$$

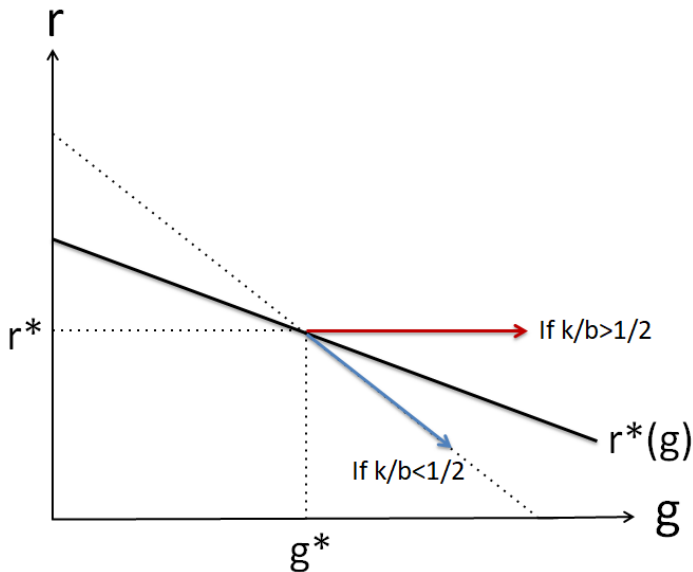
$$\Lambda_q(\delta) \equiv \frac{C(n-1)}{b} \left(1 - \delta - \sqrt{\frac{\delta(b+\delta k)}{k}} \right).$$

- (iii) If $k/b < 1/2$, then $\bar{\delta}^r > \bar{\delta}^g$ and, when $\delta \in \left[\hat{\delta}^g(g, r), \bar{\delta}^r \right)$, we have:

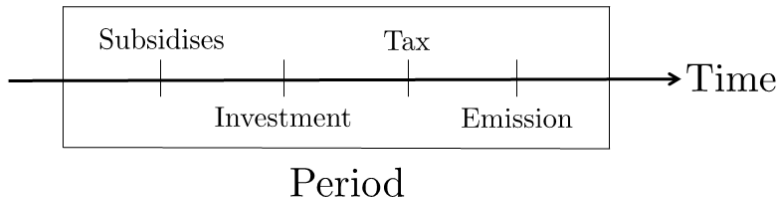
$$r = r^* - \Xi_q(\delta) < r^* \text{ and } g = g^* + \Xi_q(\delta) > g^* \text{ where}$$

$$\Xi_q(\delta) \equiv \frac{C(n-1)}{k} \left(1 - \delta - \sqrt{\frac{k + \delta^2 b}{b}} \right).$$

3. Quantity Agreements - Compliance



4. Price Agreements (Taxes and Subsidies)



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- Cooperating on r and g , or emission tax τ and investment subsidy ζ seem equivalent.
- Consumers pollute until $bd = \tau$, while investors ensure $kr - \zeta = bd = \tau$.
- For any given g , $\zeta^*(g) = 0$.
- If δ is so large that the first best can be implemented, $\zeta^*(g) = 0$.
- What happens when δ is smaller?
- When $\delta \in (\bar{\delta}^r, \bar{\delta}^g)$, d and thus τ cannot be set at the socially optimal level. I.e, $\tau < Cn$. The smaller is $\delta \in (\bar{\delta}^r, \bar{\delta}^g)$, the smaller is the equilibrium d and thus τ .
- To ensure that $kr = Cn$, $\zeta = Cn - \tau > 0$ decreases in $\delta \in (\bar{\delta}^r, \bar{\delta}^g)$.

4. Price Agreements (Taxes and Subsidies)

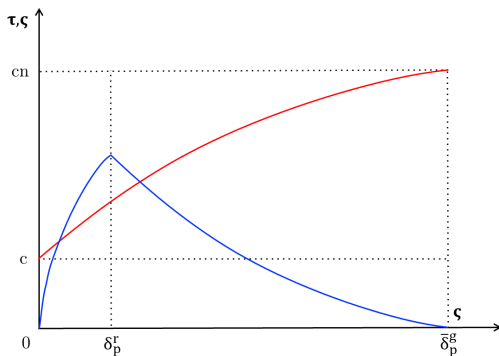


Figure: The blue (nonmonotonic) line represents the optimal investment subsidy while the red (increasing) line represents the optimal emission tax, both as functions of the discount factor.

4. Price Agreements (Taxes and Subsidies)

- **Lemma 2:** *As δ falls, CC^g binds before CC^r .*
- Why?
- When firms in country j observe a reduction in ζ_j , they anticipate BAU and low demand for tech. So, investments fall immediately, everywhere.
- **Finding 2.** If $\delta < \bar{\delta}_p^g$,

$$\tau = \tau^* - \Lambda_p(\delta) \quad \text{and} \quad \zeta = \Lambda_p(\delta), \text{ where } \Lambda_p(\delta) = b\Lambda_q(\delta).$$

- If δ falls further enough, it becomes tempting to defect also on ζ_j , which thus must fall.

4. Price Agreements (Taxes and Subsidies)

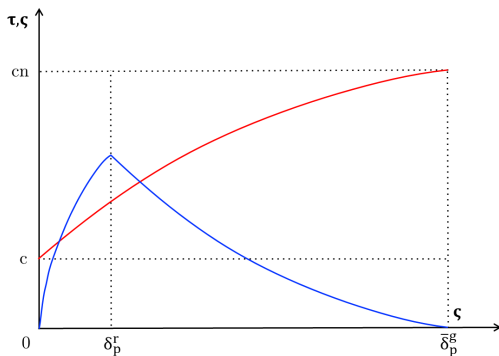


Figure: The blue (nonmonotonic) line represents the optimal investment subsidy while the red (increasing) line represents the optimal emission tax, both as functions of the discount factor.

4. Price vs. Quantity Agreements

- By comparison — which type of agreement is best?
- Why?
- The price agreement gives firm flexibility to react to other countries' defection.
- That reaction lowers investments, and makes defection less attractive.
- For this reason, the price agreement is best.
- Conclusion can be reversed with e.g. uncertainty/shocks.

5. Extensions

- Uncertainty/shocks/private information: $V \downarrow$, temptation $\uparrow$, so $r \uparrow$.
- Technological spillovers: Then, CCr might bind first even with the "price" instrument.
- Renegotiation: Punishment less severe, temptation $\uparrow$, so $r \uparrow$.
- Other types of sanctions: Harsher? More credible? $r \downarrow$.
- Time inconsistent preferences?
- Political economy?

Lessons on Compliance

- The "first best" is attainable if countries are patient or actions frequently observed
- Transparency is important
- With smaller discount factors, the technology will have a new role.
- Instead of "underinvestments" under legally binding agreements, now countries **may invest "too much"**, so that it is credible that they will comply.
- Or, if technology is fundamental (and pinning down future emission levels), countries must be punished if they invest the optimal amount!
- Intuition: Too much renewables unables them to punish other defectors.
- **Price instruments** make compliance more attractive, since other investors reach negatively after a defection at the investment policy stage.