Climate-Change Treaties: A Game-Theoretic Approach

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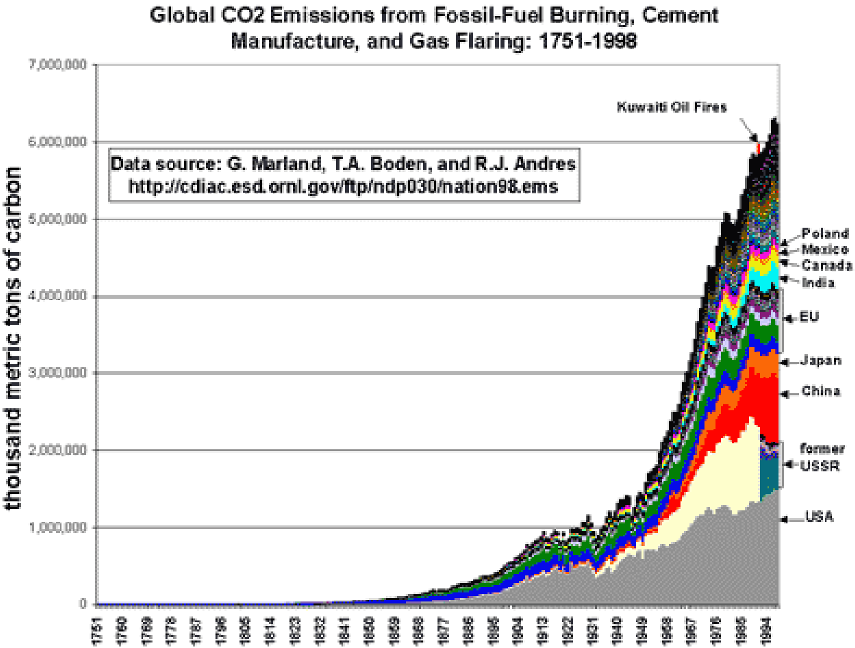
Here are four facts related to global warming, as of 2005. :
1. Average global surface temperatures have risen by 0.6C in the last 140 years.
2. Every one of the 10 warmest years in recorded history have occurred since 1990, including each year since 1997.
3. The Intergovernmental Panel on Climate Change (IPCC) predicts that if we go on as we are, by 2100 global sea levels will probably have risen by 9 to 88cm and average temperatures by between 1.5 and 5.5C.
The most frequently cited cause for this warming is the greenhouse effect - the increase in greenhouse gases (GHGs), especially CO_2, generated through the burning of fossil fuels.
4. Before the Industrial Revolution, atmospheric CO_2 concentrations were about 270-280 parts per million (ppm). They now stand at almost 380ppm, and have been rising at about 1.5ppm annually


Global CO2 Emissions from Fossil-Fuel Burning, Cement Manufacture, and Gas Flaring: 1751-1998
Data source: G. Marland, T.A. Boden, and R.J. Andres
http://cdiac.esd.ornl.gov/ftp/ndp030/nation98.ems
thousand metric tons of carbon
7,000,000
6,000,000
5,000,000
4,000,000
3,000,000
2,000,000
1,000,000
0
Kuwaiti Oil Fires
Poland
Mexico
Canada
India
EU
Japan
China
former USSR
USA
1751
1760
1769
1778
1787
1796
1805
1814
1823
1832
1841
1850
1859
1868
1877
1886
1895
1904
1913
1922
1931
1940
1949
1958
1967
1976
1985
1994

Global warming (or global climate change) is a "tragedy of the commons." It poses interesting theoretical challenges for several reasons:

1. It is international in scope, requiring international, or transnational, cooperation.
2. Dynamics are long-lasting, and reversibility is very slow.
3. Because of the long time-scale (point 2), intergenerational equity issues are important.

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3. Because of the long time-scale (point 2), intergenerational equity issues are important.
4**. Because of significant international differences in population, rates of population growth, and levels of economic development, issues of international equity are also significant.**
5. Although the scientific basis of global warming is qualitatively established, there is considerable uncertainty (and disagreement) about its dynamics and consequences.

The absence of world government implies the need for a **self-enforcing treaty** to curb global warming.
We model the situation as a **dynamic game** in which **the players are the world's countries**.
There will be many Nash equilibria of this game.
One of them is the current trajectory - **"business as usual."**
A self- enforcing treaty is also a (subgame perfect) Nash equilibrium of the game.

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We search for self-enforcing treaties that are Pareto-superior to business-as-usual.

More ambitious - second-best? first-best?

Outline of Models and Analyses

1. A dynamic model
2. Constant populations and capital stocks
   "business as usual" (BAU) - a Markov equilibrium
   Global Pareto optima (GPOs)
   Other equilibria
3. Numerical calibration and analysis

[4. Constant emission technology]

5. Ongoing and future research

A Dynamic Model

$$
\begin{aligned}
t &= \text{time period } (0, 1, 2, \text{...ad inf.}). \\
i &= \text{coutry } (1, ..., I). \\
K_i(t) &= \text{ capital stock of country } i \text{ at the beginning of period } t. \\
P_i(t) &= \text{population of country } i \text{ at the beginning of period } t. \\
e_i(t) &= \text{"energy input" of country } i \text{ in period } t. \\
a_i(t) &= \text{emission of greenhouse gas (GHG) by country } i \text{ in period } t. \\
g(t) &= \text{the global stock of GHG at the beginning of period } t. \\
f_i(t) &= \text{the "emission factor" of country } i \text{ in period } t.
\end{aligned}
$$

The initial values, $g(0)$ and $f_i(0)$, of the GHG stock and the emission factors, respectively, together with the sequences of capital stocks and populations, are exogenous. All the rest of the variables are endogenous, with each country controlling its own endogenous variables.

States and Strategies

The **state of the system** *at the beginning of period* t is

$$\begin{aligned} \mathbf{s}(t) &= [g(t), \mathbf{f}(t), \mathbf{K}(t), \mathbf{P}(t)], \\ \mathbf{f}(t) &= [f_1(t), ..., f_I(t)], \\ \mathbf{K}(t) &= [K_1(t), ..., K_I(t)], \\ \mathbf{P}(t) &= [P_1(t), ..., P_I(t)]. \end{aligned}$$

In period t each country i chooses its **action,** $[e_i(t), f_i(t+1)]$, as a function of the history of actions from periods 0 through $(t-1)$ and of states from periods 0 through t. The sequence of those functions is the country's **strategy**. A country's strategy is **stationary** if its current action depends only on the current state. The constraints on actions are:

$$\begin{aligned} 0 &\leq e_i(t), & (1) \\ \mu_i &\leq f_i(t+1) \leq f_i(t). & (2) \end{aligned}$$

System Dynamics

$$
\begin{aligned}
a_i(t) &= f_i(t)e_i(t), && (3)\\
A(t) &= \sum_i a_i(t), && (4)\\
g(t) &= \sigma g(t-1) + A(t), && (5)\\
K_i(t+1) &= H\left[K_i(t)\right], \quad K_i(t) \nearrow \text{ and unbounded in } t, && (6)\\
P_i(t+1) &= \psi_i P_i(t) + (1-\psi_i)\Psi, \quad P_i(t) \leq \Psi. && (7)
\end{aligned}
$$

Payoff Functions

The *one-period utility* (payoff) of country i in period t is:

$$\begin{aligned} u_i(t) &= Y_i[K_i(t), P_i(t), e_i(t)] && (8) \\ &\quad -\gamma_i P_i(t) g(t) - \varphi_i [f_i(t) - f_i(t+1)]. && (9) \end{aligned}$$

The corresponding *game payoff* is the sum of discounted one-period utilities,

$$v_i = \sum_{t=0}^{\infty} \delta^t u_i(t). \quad (10)$$

Assume:

$$\begin{aligned} \text{all parameters} &> 0, && (11) \\ \delta, \psi_i, \sigma, \text{ are} &< 1, && (12) \end{aligned}$$

Also, Y_i satisfies "usual economic regularity conditions."

Equilibria and Optima

A **strategy profile** is an I-tuple of strategies, one for each country.
A strategy profile is a **Nash equilibrium (NE)** if no country can increase its game payoff by *unilaterally* changing its strategy.
A **Markov-Nash equilibrium (MNE)** is a NE such that every country's strategy is stationary.
A strategy profile is a **global-Pareto-optimum (GPO)** if for some strictly positive vector $(x_1, \ldots, x_I)$. it maximizes the sum $\sum_i x_i v_i$ in the set of all strategy profiles. *[Note: terminology warning!]*

Constant Populations and Capital Stocks

Country payoff function in perod t:

$$u_i(t) = Y_i[e_i(t)] - \gamma_i g(t) - \varphi_i[f_i(t) - f_i(t+1)]. \tag{13}$$

Business as Usual Equilibrium (BAU)

A Markov equilibrium.
Each country changes its emission factor in one period to its lower bound, or never.
Each country's emission depends only on its own current emission factor.

Global Pareto Optimum (GPO)

Stationary strategies.
Qualitatively similar to BAU, but quantitatively different.

Comparison of BAU and GPO

1. For each country, for the same emission factor, BAU emission $>$ GPO emission.
2. For each country, BAU emission factor $\geq$ GPO emission factor.
3. Starting from a GPO, each country will want to increase its emissions **unilaterally** by at least a small amount.
4. There is an open set of vectors (x_i) of strictly positive weights such that the corresponding GPO is strictly Pareto superior to the BAU.

Other Equilibria
Trigger Strategy Profiles with BAU Reversion

Given a GPO that Pareto dominates the BAU, suppose that the **"norm"** is for every country *i* to use its GPO emission.
A **defection** occurs at period *t* if some country emits more than its GPO emission. After a defection, if any, every country uses its BAU emission forever: [Grim!]

Other Equilibria (continued)

A Positive Result. If $\mu_i > 0$ for all i, then for any set of strictly positive weights, and δ sufficiently close to unity, the GPO can be sustained as the outcome of a "trigger-strategy" equilibrium with the threat of reversion to the BAU.

A Negative Result. If $\mu_i = 0$ for all i, and in the GPO all countries reduce their emission factors to zero, then for all $\delta < 1$ the GPO cannot be sustained as the outcome of any equilibrium. [Recall assumption that emission factor reduction is irreversible.]

[More know about other equilibria in the case of fixed emission factors.]

Numerical Examples

Benchmark Case.

Initial year = 1998. $\delta = 0.97$

Damage cost coefficients from Fankhauser (1995).

"Cobb-Douglas" production functions.

For each country, population & capital stocks constant in time.

Calibrated so that BAU matches available data and estimates for 1998.

Welfare in 1990 US dollars. Emissions in gigatons of carbon.

Benchmark Case

Region	BAU emissions GtC	GPO emissions % decrease	GPO value % increase
USA	1.5	66	0.32
W Eur.	0.86	66	0.35
OHI	0.59	66	0.41
E Eur	0,74	72	0.54
MI	0.41	67	1.47
LMI	0.58	69	1.31
China	0.85	69	3.04
LI	0.66	69	1.37
total	6.18	68	0.63

Sensitivity Analysis

Discount factor	Fankhauser Damage Cost Coeff.	5 $\times$ Fankhauser Damage Cost Coeff.
$\delta = 0.97$	**68**	**76**
	0.63	**3.95**
$\delta = 0.995$	**72**	**83**
	1.98	**12.79**

Upper: GPO % emissions decreases

Lower: GPO % value increases

Extensions

Complete analysis and calibration of initial model.
Nonlinearities
Uncertainty

Extensions (continued)

Complete analysis and calibration of initial model.

Nonlinearities

Uncertainty

Strategic choices of:

- **Technology transfer**
- **Other side payments**

An International Bank for the Environment

Moving to a new equilibrium

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The Case of Fixed Emission Factors
The Equilibrium Payoff Correspondence

There exists a compact subset U of $\mathcal{R}^I$ such that, for any subgame-perfect equilibrium (SPE), the value function for player i is

$$V_i(g) = u_i - w_i g,$$

where the vector $u = (u_1, ..., u_I) \in U$ and, as before,

$$w_i = \frac{\gamma_i}{1 - \delta\sigma}.$$

Greenhouse Trap Equilibria

For expositional simplicity assume symmetry of countries and the GPO with equal weights.
All countries have the same BAU emission, a^*, and the same GPO emission, $\hat{a}$. Let $\hat{g}$ be the steady-state GPO stock of GHG.
The greenhouse-trap strategy profile is:

$$a(g) = \begin{cases} (\hat{g} - \sigma g)/I, & \text{for } g \leq \hat{g}, \\ a^*, & \text{for } g > \hat{g}. \end{cases}$$

Greenhouse Trap Equilibria (continued)

Assume that

$$\frac{a^*}{\widehat{a}} > \max(\frac{I}{I-1}, \frac{1}{1-\sigma});$$

then there is a discount factor - say $\widehat{\delta}$ - such that for all $\delta \geq \widehat{\delta}$ the greenhouse-trap strategy profile is a Markov equilibrium. In this equilibrium the GHG level converges in one period to the Pareto optimal steady state $\widehat{g}$ if the initial level is below $\widehat{g}$, whereas it converges asymptotically to the BAU steady state g^* if the initial level is above $\widehat{g}$.

[Variations on this theme....]