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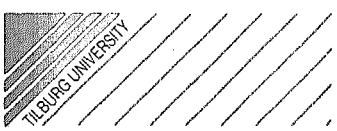

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A differential game of international pollution control

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Abstract: Pollution is an inevitable by-product of production and damages the environment. The trade-off between production as a good and pollution as a bad over time can be analysed in the framework of a control model, which yields a path of emission charges that force the producers to behave in a socially optimal way. Pollution that crosses national borders calls for international coordination of emission charges. In order to estimate the benefits of coordination one must use a realistic non-cooperative equilibrium concept. A natural extension of the control model implies unrealistic assumptions on information and commitment, and under-estimates the damage to the environment of not coordinating emission charges. In this note the more realistic subgame-perfect non-cooperative equilibrium is derived, which reinforces the case for international agreements on pollution control.

Keywords: Differential games; economics; pollution; open-loop/feedback; non-cooperative/cooperative.

1. Introduction

Many production processes damage the environment and this is the subject of increasing concern in the world of today. There exists a trade-off between the benefits of production and the disutility of pollution as an inevitable by-product of production. Pollution is an externality. In the absence of private property rights for a clean environment and associated markets for pollution rights, production decisions lead to inefficient outcomes with too much production and pollution. Trying to enforce these rights is difficult and implies high administrative costs. It is often better that the government relies on taxes and subsidies in an attempt to bring about efficient production decisions. Dasgupta [2] sets up a control model to analyse the intertemporal trade-off between the benefits of production and the resulting damage to the environment. Such a model yields optimal emission charges, which correspond to the social price of a unit of pollution and, hence, ensure that production decisions are efficient.

Many pollutants (e.g. carbon dioxide) cross over national borders, which causes another externality. The analysis of Dasgupta [2] can be repeated with respect to a social welfare index for all countries together. As a result emission charges are found, which lead to efficient outcomes and, therefore, should be the aim of an international agreement. These results have to be compared with the non-cooperative outcome in order to estimate the benefits of international policy coordination. The non-cooperative outcome can be found by solving the control problems for each country separately and by using the Nash equilibrium concept. At this point, however, one has to be careful. When the Pontryagin technique is used, as is done in Dasgupta [2], the open-loop Nash equilibrium (Başar and Olsder [1]) is found. Conceptually it is assumed now that the countries do not have information on the concentration levels of pollutants and commit themselves forever to an initially chosen path of emission charges. It seems more realistic to assume that countries do have information on the concentration levels of pollutants and can reconsider their emission charges at any point in time. Therefore, in this note the feedback Nash or

subgame-perfect Markov equilibrium is derived. It is shown that the subgame-perfect Markov equilibrium leads to a higher concentration level of pollutants and lower emission charges than the open-loop Nash equilibrium. It follows that as a consequence of unrealistic assumptions on the available information and the period of commitment the damage to the natural environment of not coordinating emission charges is under-estimated.

Section 2 describes the multi-country version of the pollution control model in Dasgupta [2]. Furthermore, the model is extended with the possibility that countries make an effort to clean up the environment at a certain cost. Section 3 describes the outcome under international coordination and under the non-cooperative open-loop Nash equilibrium. In Section 4 the feedback Nash or subgame-perfect Markov equilibrium is derived. Furthermore, the main result of this note is given, which states that the benefits of international coordination are under-estimated unless this more realistic equilibrium concept is employed in the analysis. Section 5 concludes the note with a summary and with suggestions for important extensions of the basic international pollution control model.

2. Multi-country pollution control model

There are N countries of equal size denoted by the subscripts $i = 1, \ldots, N$. The production, Y_i, of each country i yields as an inevitable by-product a flow of pollutants, αY_i, where $\alpha > 0$ denotes the emission-output ratio. The pollutants spread out over all countries and increase the average stock of pollutants, S, which slowly dissolves at a rate δ. This concentration level of pollutants damages the natural environment of each country according to a convex social damage function $D(S)$. This model effectively describes, for example, the greenhouse effect due to the emission of carbon dioxide. For other forms of pollution, such as the "downstream" pollution due to the dumping of toxic waste in the river Rhine, an asymmetric set-up is required. To simplify matters, it is assumed that the emission-output ratio is fixed and cannot be lowered by investment in clean technology. There is also no investment in physical capital for growth or in purification plants, but countries can make an effort, E_i, at a cost, $C(E_i)$, $C' > 0$, $C'' > 0$, in order to reduce the concentration level of pollutants. Apart from the negative externality of pollution also a positive externality can occur, because cleaning up is a public good as all countries benefit from it. The net social benefit of production, Y_i, is given by a concave function, $B(Y_i)$. Formally, the government of country i aims at a production path, $Y_i(t)$, and a path of efforts, $E_i(t)$, in order to maximise social welfare,

$$W_i \equiv \int_0^\infty \exp(-rt)\left[B(Y_i(t)) - C(E_i(t)) - D(S(t))\right] \mathrm{d}t, \quad i = 1, \ldots, N, \tag{1}$$

where $r > 0$ denotes the social rate of discount, subject to the change over time of the concentration level of pollutants,

$$\dot{S} = (\alpha/N)\left(\sum_{i=1}^{N} Y_i\right) - \delta S - (1/N)\left(\sum_{i=1}^{N} E_i\right), \quad S(0) = S_0, \tag{2}$$

where $\delta \geq 0$ denotes the constant rate of degradation. Since there are no markets for pollution rights and individual atomistic agents cannot influence the level of total pollution, the market outcome simply corresponds to $E_i = 0$ and $Y_i = Y_M = \operatorname{argmax}(B(Y))$ which satisfies $B'(Y_M) = 0$.

3. Cooperative and non-cooperative emission charges

Under international coordination, denoted by the subscript I, the countries jointly aim at production levels $\{Y_i(t), t \geq 0, i = 1, \ldots, N\}$ and efforts $\{E_i(t), t \geq 0, i = 1, \ldots, N\}$ in order to maximise global

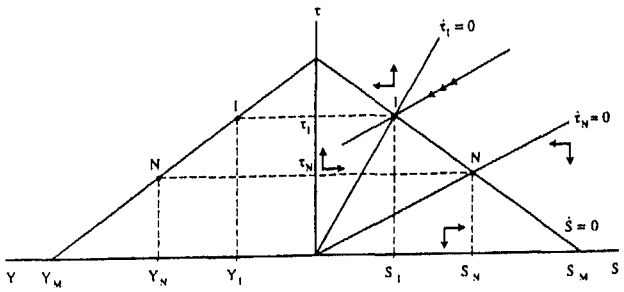

Fig. 1.

welfare $W \equiv \sum_{i=1}^{N} W_i$. Because of symmetry the outcomes are the same for each country. The optimality conditions are:

$$B'(Y) = (\alpha/N)\tau \quad \text{or} \quad Y = \phi(\alpha\tau/N), \quad \phi' = 1/B'' < 0, \tag{3}$$

$$C'(E) = (1/N)\tau \quad \text{or} \quad E = \psi(\tau/N), \quad \psi' = 1/C'' > 0, \tag{4}$$

$$\dot{\tau} = (r+\delta)\tau - ND'(S), \qquad \lim_{t\to\infty} \exp(-rt)\tau(t)S(t) = 0, \tag{5}$$

where τ denotes the optimal emission charge (or minus the shadow price of the concentration level of pollutants). When the governments jointly levy an average emission charge τ per unit of pollution and give a subsidy τ/N per unit of private effort to clean up the environment, private agents maximise $B(Y_i) - C(E_i) - (\alpha/N)\tau Y_i + (1/N)\tau E_i$, which forces the market to behave in a socially optimal way. Substitution of (3) and (4) in (2) yields the controlled dynamic development of the concentration level of pollutants

$$\dot{S} = \alpha\phi(\alpha\tau/N) - \delta S - \psi(\tau/N), \quad S(0) = S_0. \tag{6}$$

The non-cooperative open-loop Nash equilibrium, denoted by the subscript N, is given by (3) and (4), but with (5) replaced by

$$\dot{\tau} = (r+\delta)\tau - D'(S), \qquad \lim_{t\to\infty} \exp(-rt)\tau(t)S(t) = 0, \tag{5'}$$

so that the marginal social damage of an additional unit of production in the non-cooperative outcome is one N-th of the damage under international coordination.

The systems of differential equations (5)–(6) and (5')–(6) both have a negative Jacobian, so the steady states are saddlepoints. The phase diagrams are drawn in Figure 1. Obviously, the steady-state value of the concentration level of pollutants under international coordination is lower than under the non-cooperative open-loop Nash outcome whilst it is highest under the market outcome, $S_M > S_N > S_I$. Because $\phi' < 0$ and $\psi' > 0$, it follows from (6) that the opposite holds for the corresponding emission charges, $\tau_I > \tau_N > \tau_M = 0$. Furthermore, it follows from $\phi' < 0$ that $Y_I < Y_N < Y_M$, and from $\psi' > 0$ that $E_I > E_N > E_M = 0$. Hence, the market fails to deliver pollution control whilst absence of international policy coordination leads to too low emission charges and not enough abatement activities.

4. Subgame-perfect Markov outcome

The non-cooperative open-loop Nash outcome yields strategies, which are a function of time and the initial concentration level of pollutants, S_0, and which are chosen at time 0 for all future points in time.

Hence, countries do not condition their strategies on observations of the concentration level of pollutants over time and are committed to stick to their initially chosen policies forever (Reinganum and Stokey [4]). It seems more realistic to use the feedback Nash or subgame-perfect Markov equilibrium concept (Başar and Olsder [1]; Fershtman [3]; de Zeeuw and van der Ploeg [5]), denoted by the subscript F, in which the countries condition their strategies on the current observation of the concentration level of pollutants and are not committed to any future policy actions. This means that, even when countries deviate from the equilibrium path, it is rational to carry out announced policies if called upon to do so at some point in the future. In technical terms, Bellman's dynamic programming technique is used instead of Pontryagin's maximum principle. In order to obtain analytical results, attention is focused on quadratic objective functions: $B(Y)=\beta Y-\frac{1}{2}Y^2$, $D(S)=\frac{1}{2}\gamma S^2$ and $C(E)=\frac{1}{2}\theta E^2$. The Hamilton–Jacobi–Bellman equation for country i, $i=1,\ldots,N$, becomes

$$rV_i(S,t)-\partial V_i(S,t)/\partial t=\max\left\{\beta Y_i-\tfrac{1}{2}Y_i^2-\tfrac{1}{2}\theta E_i^2-\tfrac{1}{2}\gamma S^2+\left[\partial V_i(S,t)/\partial S\right]\left[(\alpha/N)\sum_{j=1}^{N}Y_j-\delta S-(1/N)\sum_{j=1}^{N}E_j\right]\right\}, \tag{7}$$

where V_i denotes the value function, which gives the equilibrium value of social welfare from time t onwards, starting with concentration level of pollutants S. Because of symmetry again the outcomes are the same for each country. The equilibrium strategies are given by

$$Y(S,t)=\phi(-(\alpha/N)\,\partial V(S,t)/\partial S)=\beta+(\alpha/N)\,\partial V(S,t)/\partial S, \tag{8}$$

$$E(S,t)=\psi(-(1/N)\,\partial V(S,t)/\partial S)=-(1/N\theta)\,\partial V(S,t)/\partial S. \tag{9}$$

The emission charge τ corresponds to $-\partial V(S,t)/\partial S$ (cf. (3), (4), and (5)). Substituting (8) and (9) in (7), postulating a concave quadratic form for the value function, $V(S,t)=\sigma_0(t)-\sigma_1(t)S-\frac{1}{2}\sigma_2(t)S^2$, $\sigma_2(t)>0$, so that $\partial V(S,t)/\partial S=-\sigma_1(t)-\sigma_2(t)S$, and equating coefficients of S and S^2 leads to a system of differential equations in σ_1 and σ_2. The saddlepoint solution of this system is given by

$$\sigma_1=\left\{\frac{\alpha\beta\sigma_2}{r+\delta+\left[\alpha^2+(1/\theta)\right]\left(\frac{2N-1}{N^2}\right)\sigma_2}\right\}>0, \tag{10}$$

$$\sigma_2=\left\{\frac{-(r+2\delta)+\left\{(r+2\delta)^2+4\gamma\left[\alpha^2+(1/\theta)\right]\left(\frac{2N-1}{N^2}\right)\right\}^{1/2}}{2\left[\alpha^2+(1/\theta)\right]\left(\frac{2N-1}{N^2}\right)}\right\}>0. \tag{11}$$

The resulting differential equation for the concentration level,

$$\dot{S}=\left\{\alpha\beta-\left[\alpha^2+(1/\theta)\right](\sigma_1/N)\right\}-\left\{\delta+\left[\alpha^2+(1/\theta)\right](\sigma_2/N)\right\}S, \tag{12}$$

is stable and has the steady-state value

$$S_F=\left\{\frac{\alpha\beta-\left[\alpha^2+(1/\theta)\right](\sigma_1/N)}{\delta+\left[\alpha^2+(1/\theta)\right](\sigma_2/N)}\right\}. \tag{13}$$

In order to be able to compare this with previous results, the values of S_1, S_N and S_M have to be

calculated for the same quadratic benefit, damage and cost functions. Straightforward calculation yields:

$$S_I = \left(\frac{\alpha\beta}{\delta + [\alpha^2 + (1/\theta)]\left(\frac{\gamma}{r+\delta}\right)} \right) < S_N = \left(\frac{\alpha\beta}{\delta + [\alpha^2 + (1/\theta)]\left(\frac{\gamma}{N(r+\delta)}\right)} \right) < S_M = \frac{\alpha\beta}{\delta}. \tag{14}$$

Proposition. $S_I < S_N < S_F < S_M$.

Proof. $S_F < S_M$ follows immediately from (10)–(14). Since

$$\alpha\beta - [\alpha^2 + (1/\theta)](\sigma_1/N) = \alpha\beta\left(\frac{r+\delta+[\alpha^2+(1/\theta)][(N-1)/N^2]\sigma_2}{r+\delta+[\alpha^2+(1/\theta)][(2N-1)/N^2]\sigma_2} \right), \tag{15}$$

in order to prove $S_N < S_F$, one has to prove

$$\frac{r+\delta+[\alpha^2+(1/\theta)][(2N-1)/N^2]\sigma_2}{\delta+([\alpha^2+(1/\theta)]\gamma/N(r+\delta))} < \frac{r+\delta+[\alpha^2+(1/\theta)][(N-1)/N^2]\sigma_2}{\delta+[\alpha^2+(1/\theta)](\sigma_2/N)} \tag{16}$$

or

$$(r+2\delta)\sigma_2 + [\alpha^2+(1/\theta)]\left(\frac{2N-1}{N^2}\right)\sigma_2^2 - \gamma < \left(\frac{[\alpha^2+(1/\theta)]\gamma}{r+\delta}\right)\left(\frac{N-1}{N^2}\right)\sigma_2. \tag{17}$$

The left-hand side is zero while the right-hand side is strictly positive, which completes the proof. □

Corollary. $\tau_I > \tau_N > \tau_F > \tau_M = 0$; $Y_I < Y_N < Y_F < Y_M$; $E_I > E_N > E_F > E_M = 0$.

Proof. The steady-state relations between τ and S, Y and τ, and E and τ are monotonic. □

It is easy to explain why the subgame-perfect Markov outcome leads to a higher concentration level of pollutants than the open-loop Nash outcome. Each country reasons that the other countries will react to an increase in the concentration level of pollutants with lower production levels and more efforts to clean up, according to the contingent strategies given by (8) and (9). These reactions partly off-set the initial increase in pollution. As a result of this reasoning the equilibrium outcome for the concentration level of pollutants is higher, because the marginal damage to the natural environment is valued lower than in the open-loop case. The proposition leads to the important conclusion that the environmental benefits of international coordination are higher when the more realistic non-cooperative equilibrium concept is used. Unrealistic assumptions on information and commitment under-estimate the damage to the environment of not coordinating emission charges.

5. Conclusion

This note derives cooperative and non-cooperative outcomes of the game of international pollution control. Absence of international policy coordination leads to too low emission charges, insufficient abatement activities and too much pollution. The subgame-perfect Markov equilibrium has more realistic assumptions about information and commitment than the open-loop Nash equilibrium, but leads to more pollution. Hence, the open-loop Nash equilibrium under-estimates the benefits of international coordination. Further research will be directed towards extending the basic pollution control model to allow for other abatement activities such as investment in clean technology and in purification plants. This allows

one to ask whether it is better to grow fast in order to have resources for investment in abatement or to grow slow in order to pollute less.

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