International Aspects of Pollution Control*

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Abstract. Pollution is a by-product of production, is only gradually dissolved by the environment, and crosses national borders. The market outcome ignores the adverse effects of pollution and thus yields higher levels of output and pollution than would prevail under a supranational social planner which does care about pollution. In practice, governments often do not cooperate and this leads to outcomes of pollution and production in between the market outcomes and the outcomes under supra-national social planning. Absence of precommitment leads to lower emission charges, less cleaning-up activities and more pollution. Appropriate levels of emission charges under the various outcomes are a result of this analysis. Attention is also paid to investment in clean technology. The debate between optimists, who believe that higher production is compatible with sound environmental policy, and pessimists can be analysed in this way.

Key words. Pollution control, international policy games.

1. Introduction

Pollution is an inevitable by-product of production and damages the environment. Pollution also traverses national borders and is therefore an international problem. Market outcomes are efficient when all agents are price takers and when a complete set of contingent markets exists for each and every commodity (e.g., Malinvaud, 1972), but the absence of private property rights for a clean environment and associated markets for pollution rights imply that market outcomes will be inefficient and there will be too much production and pollution (e.g., Dasgupta, 1982). Three main approaches to environmental policy can be distinguished. The first is to enforce property rights with binding quota restrictions on the amount produced. The problems with such emission standards are that they are difficult to enforce,

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that they are associated with high administrative costs, and that they lead to economic inefficiencies. The second approach is to rely on Pigouvian taxes and subsidies. Such emission charges correspond to the social price of a unit of pollution and thus ensure that polluters pay for the damage they impose on the environment and that the non-cooperative market outcome is efficient. The final approach is to explicitly fill in the missing markets by introducing markets for pollution rights. Here attention is mostly focussed on the second approach.

This paper characterises and compares the optimal emission charges when each country sets its environmental policy in a non-cooperative manner and when all countries coordinate their actions and set their environmental policy jointly. It also discusses the potential gains from the international coordination of emission charges.[1] The benchmark corresponds to a decentralised market outcome, which is relevant when none of the countries pursues environmental policies. Section 2 starts with a simple static multi-country model with flow damage of pollution. International policy coordination leads to higher emission charges and consequently lower levels of production. The remainder of the paper deals with the intricacies of differential game theory which arise when one considers the stock damage of environmental pollution. Section 3 sets up the model. Section 4 discusses the outcome under international coordination of emission charges. Sections 5 and 6 discuss the non-cooperative emission charges associated with, respectively, the open-loop Nash and the subgame-perfect (or feedback) Nash equilibrium. The open-loop Nash equilibrium leads to lower levels of production and pollutants and to higher emission charges than the subgame-perfect Nash equilibrium, and is therefore closer to the outcome under international policy coordination. However, because the open-loop solution concept is less realistic, this in fact means that the open-loop Nash equilibrium seriously underestimates the damage to the environment of not coordinating emission charges, and thus underestimates the potential benefits of international policy coordination. Section 7 discusses the potential benefits of efforts to clean up the environment and finds that cleaning-up activities do not occur if matters are left to the market and are highest under international policy coordination. Also, the open-loop Nash equilibrium overestimates the level of cleaning-up activities compared with the subgame-perfect Nash equilibrium. Section 8 discusses investment in clean technology and reducing the stock of pollutants and relates this to the environmental debate between optimists, who believe that higher production benefits a sound environmental policy, and pessimists, who believe that national production should fall for otherwise the environment will suffer irrepairable damage. Section 9 concludes the paper.

2. Flow Damage of Pollution

There are N countries denoted with the subscripts $i = 1, \ldots, N$. There is no investment in physical capital, so what each country produces is consumed.[2] The net social benefits of production of country i, say Y_i, are given by $B(Y_i)$, $B'' < 0$. Net benefits initially increase with the level of production as this means a higher level of consumption, but at high levels of consumption the marginal utility of consumption is much lower than the marginal utility of leasure so that net benefits decrease with the level of production. In the decentralised market outcome agents hardly care about the environment, because their individual actions have little effect on total pollution. It is therefore assumed that the market outcome corresponds to $Y_i = Y_M \equiv \arg(\max_Y B(Y))$ and satisfies $B'(Y_M) = 0$. This is, of course, a simplified view of the world (see, for a more comprehensive discussion of these issues, Folmer and van Ierland, 1989).

However, pollution is an inevitable by-product of production, αY_i, where $\alpha > 0$ denotes the emission-output ratio. The emission-output ratio is assumed to be constant; Section 7 discusses what happens when it can be reduced by investment in new technology. Pollution affects all countries immediately and, for the time being, it is assumed that the flow of pollution $F \equiv (\alpha/N)\ (\Sigma_{j=1}^{N} Y_j)$, affects social welfare directly. To be precise, $D(F)$, $D' > 0$, $D'' \geqslant 0$, denotes the social damage caused by the emission of pollutants by all of the countries concerned. The marginal social damage increases with the level of pollution. The definition of the flow of pollution, F, makes the analysis symmetric. Asymmetries such as "downstream" pollution are dealt with in the Appendix for the more interesting case of stock damage, which is the subject of the next section. An example of pollution that is detrimental to welfare as a flow is noise, although this does not seem very relevant in an international context.

When the governments engage in pollution control, two outcomes should be distinguished. The first is the non-cooperative Nash—Cournot outcome (denoted by the subscript N) in which each government chooses its level of production to maximise social welfare, $B(Y_i) - D(F)$, taking the actions of the other governments as given. Each government then sets the marginal benefits of an additional unit of production equal to its marginal social damage. Symmetry yields:

$$B'(Y_N) = (\alpha/N)D'(\alpha Y_N). \tag{2.1}$$

The second outcome prevails under international policy coordination (denoted by the subscript I), which is relevant when each government internalises the adverse effects of higher production and pollution on the welfare of the other countries. Symmetry yields:

$$B'(Y_I) = \alpha D'(\alpha Y_I). \tag{2.2}$$

Figure 1 compares the various outcomes. It is clear that leaving matters to the market leads to the highest level of production and pollution, whilst international coordination of emission charges leads to the lowest level of production and pollution. The optimal emission charges per unit of pollution, $P(Y_i) = (\alpha/N)Y_i$, are $\tau_N \equiv D'(\alpha Y_N)$ and $\tau_I \equiv N\,D'(\alpha Y_I)$, respectively, and the revenues from these levies are redistributed in a lump-fashion. The market then sustains the social optimal outcomes, because when individual agents maximise $B(Y_i) - \tau_N P(Y_i)$ or $B(Y_i) - \tau_I P(Y_i)$ the economy ends up with $Y_i = Y_N$ or $Y_i = Y_I$, respectively. The main results can be summarised by $Y_I < Y_N < Y_M$ and $\tau_I > \tau_N > \tau_M \equiv 0$. Failing to coordinate emission charges leads to too much pollution.

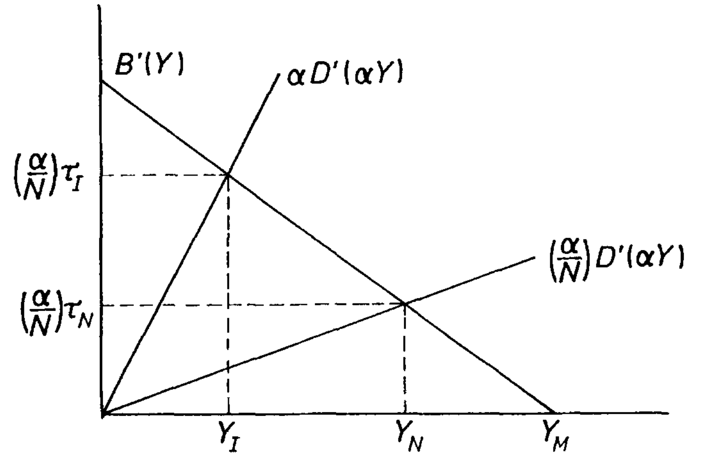

Fig. 1. International coordination of environmental policies with flow damage of pollution.

3. Stock Damage of Pollution[3]

The main thrust of the present paper is concerned with the stock rather than the flow damage of pollution. Assume therefore that the concentration level of pollutants in the environment changes over time according to:

$$\dot{S} = (\alpha/N)\left(\sum_{i=1}^{N} Y_i\right) - \delta S, \quad S(0) = S_0, \tag{3.1}$$

where $\delta \geqslant 0$ denotes the depreciation rate of the pollution concentration. Some pollutants (e.g., pesticides like DDT) are degraded at a very slow rate, others (e.g., herbicides) at a much faster rate. Ecologists warn of the danger that, when the concentration level becomes too large, pollutants become non-degradable, but here attention is focussed on a constant depreciation rate. The concentration of the pollutant can also be decrased by cleaning up the environment, but this will not be discussed until Sections 7 and 8. The main externality arises, because all countries contribute to pollution of the world.

This is not unreasonable for pollution of the air (e.g., the stock of SO_2 in the air). In general, it is more reasonable to assume that production at home pollutes the environment more at home than abroad, but this modification does not alter the qualitative nature of the steady-state results (see Appendix).

The welfare function of government i is given by

$$W_i \equiv \int_0^\infty \exp(-rt)[B(Y_i(t)) - D(S(t))]\, dt, \tag{3.2}$$

where r denotes the social rate of discount (or the consumption rate of interest) and $D(S)$, $D' > 0$, $D'' \geqslant 0$, denotes the social damage caused by a high concentration of pollutants. The damage can be direct (e.g., the effect of polluted air on health) or indirect through production elsewhere (e.g., the effect of polluted air on laundry companies or on agricultural enterprises). Some pollutants display threshold effects (e.g., below a certain level of concentration of smog trees survive, but above this level trees do not survive), but such non-convexities will not be considered.

4. International Coordination of Emission Charges

Under international coordination of environmental policies denoted by the subscript I, the countries jointly choose $\{Y_1(t), \ldots, Y_N(t),\ t \geqslant 0\}$, to maximise global welfare $W \equiv (\Sigma_{i=1}^N W_i)$ subject to (3.1)—(3.2). This yields the following optimality conditions:

$$B'(Y_I(t)) = (\alpha/N)\tau_I(t), \quad t \geqslant 0 \tag{4.1}$$

$$ND'(S_I(t)) - \delta\tau_I(t) + \dot{\tau}_I(t) = r\tau_I(t), \quad t \geqslant 0 \tag{4.2}$$

where τ denotes the optimal emission charge. The shadow price of the concentration level (the co-state variable of the optimal control problem), corresponds to the negative of the optimal emission charge, so τ can also be interpreted as the marginal loss in welfare arising from a unit increase in the concentration level of the pollutant. Equation (4.1) says that the marginal benefit of production, $B'(Y_I)$, should then equal the marginal damage arising from a higher concentration level of pollutants caused by an additional unit of production, $(\alpha/N)\tau_I$. The concentration level of the pollutant is a stock with a negative social value, $-\tau_I$. In equilibrium the social rate of return on holding this "asset", i.e., the marginal social damage for all countries concerned minus the rate of depreciation plus the expected capital loss on this asset, should equal the market rate of return on any other asset, r. This condition corresponds to equation (4.2). It is in principle no different from the arbitrage condition found in the theory of investment (which says that the marginal product of capital should equal the rental charge plus the depreciation charge). Equation (4.1) yields the optimal level of production as a negative function of the product of the emission-output ratio and the emission charge, say $Y_I = \phi(\alpha\tau_I/N)$, $\phi' = 1/B'' < 0$, so that the development of the concentration level and the emission charge can be described by:

$$\dot{S}_I = \alpha\phi(\alpha\tau_I/N) - \delta S_I, \quad S_I(0) = S_0 \tag{4.3}$$

$$\dot{\tau}_I = (r + \delta)\tau_I - N D'(S_I). \tag{4.4}$$

The determinant of the system (4.3)–(4.4), $-\delta(r + \delta) + \alpha^2 D''\phi'$, is negative, since S is predetermined and τ_I is unconstrained by its past history. The phase diagram presented in Figure 2 confirms this saddlepoint property. It is clear that the concentration level of the pollutant and optimal emission charges move up and down together. An environmental disaster causes an increase in the concentration level of the pollutant (a move from I to A). The governments immediately respond to the disaster together by increasing the emission charges (a move from A to B). The private sector produces, consumes and thus pollutes less. Along the saddlepath, SS, the concentration level and emission charges diminish until everything is back to normal again (a move from B to I). It is obvious from Figure 2 that the market outcome, which prevails when there are no emission charges, leads to higher production and pollution than the outcome under international coordination of emission charges.

Obviously, when the governments jointly set an average emission charge of τ_I per unit of pollution, say $P(Y_i) = (\alpha/N)Y_i$, $i = 1, \ldots, N$, private agents choose Y_i to maximise $B(Y_i) - \tau_I P(Y_i)$ which yields (4.1) and thus the market is forced to behave in a socially optimal way. The revenues of the emission charges are redistributed in a lump-sum fashion and everyone is better off. This is effectively the same as introducing the missing markets for pollution rights, because in an economy with perfect information the optimal emission charges should correspond to the prices pollution rights fetch on the open market.

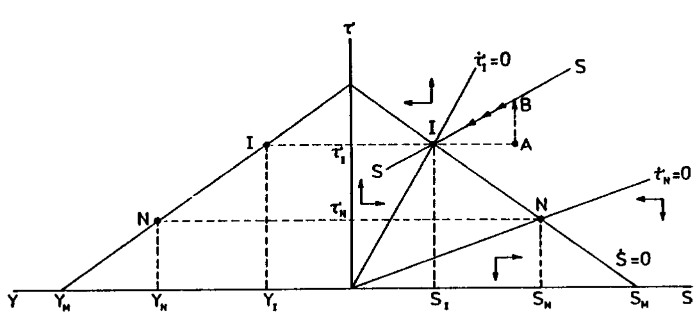

Fig. 2. Optimal emission charges and pollution management.

5. Non-Cooperative Emission Charges: Open-Loop Information Sets

Now consider the situation where individual governments set their environmental policy without taking into account the adverse effects of higher levels of production and consumption on the social welfare of other countries. An appropriate solution requires the use of differential game theory (e.g., Başar and Olsder, 1982), which has previously been used in the theory of oligopoly extraction of a common renewable property resource (e.g., Smith, 1968; Reinganum and Stokey, 1985; van der Ploeg, 1987). The first non-cooperative solution concept considered is the open-loop Nash equilibrium (indicated by the subscript N).[4] The optimal production levels and emission charges of each country are conditioned on the initial concentration level of pollutants, S_0, and time, and countries are supposed to stick to their policies. This corresponds to open-loop information patterns and to infinite periods of commitment (cf., Reinganum and Stokey, 1985). Each country takes the environmental policies of the other countries as given. This yields in symmetric equilibrium:

$$\dot{S}_N = \alpha\phi(\alpha\tau_N/N) - \delta S_N, \quad S_N(0) = S_0 \tag{5.1}$$

$$\dot{\tau}_N = (r + \delta)\tau_N - D'(S_N). \tag{5.2}$$

The main difference arises from the marginal social damage of an additional unit of production being only one N-th of that in the cooperative outcome. This means that in Figure 2 the slope of the $\dot{\tau}_N = 0$ locus is N times smaller than the slope of the $\dot{\tau}_I = 0$ locus, so that the non-cooperative open-loop Nash equilibrium has in the steady state a higher concentration level of pollutants and a lower emission charge than the cooperative equilibrium. The reason is that, in the absence of international policy coordination, each country ignores the adverse effects on foreign social welfare of an additional unit of production and pollution and therefore produces too much. Non-cooperative setting of emission charges is of course better than leaving matters to the market, so that $S_I(\infty) < S_N(\infty) < S_M(\infty)$ and $\tau_I(\infty) > \tau_N(\infty) > \tau_M(\infty) = 0$.

For future reference, it is useful to give an explicit solution for the case that the net social benefits function and the social damage function are quadratic, say $B(Y) = \beta Y - \frac{1}{2}Y^2$ and $B(S) = \frac{1}{2}\gamma S^2$:[5]

$$S_I(\infty) = \left(\frac{\alpha\beta}{\delta + \left(\frac{\alpha^2\gamma}{r+\delta}\right)}\right) < S_N(\infty) = \left(\frac{\alpha\beta}{\delta + \left(\frac{\alpha^2\gamma}{N(r+\delta)}\right)}\right) <$$

$$S_M(\infty) = \left(\frac{\alpha\beta}{\delta}\right). \tag{5.3}$$

Note that, as the number of countries becomes larger, the non-cooperative open-loop equilibrium values for the concentration level of pollutants and the levels of production converge to the market values, even though the non-cooperative emission charges converge to a finite number, $\gamma\alpha\beta/\delta(r+\delta)$.

When the governments jointly set an emission charge of τ_N per unit of pollution, private agents choose Y_i to maximise $B(Y_i) - \tau_N P(Y_i)$. This is the Pigouvian tax scheme for the case of open-loop information patterns and infinite periods of commitment. Since the emission charges are lower than in the cooperative outcome, there is excessive pollution.

6. Non-Cooperative Emission Charges: Subgame-Perfect Outcome

The problem with the open-loop Nash equilibrium solution is that it relies on unrealistic information sets and an infinite period of commitment. It is much more realistic to assume that countries can condition today's production decisions on today's concentration level of pollutants. In that case, the appropriate non-cooperative solution concept is the feedback Nash equilibrium or the subgame-perfect (Markov) outcome (denoted by a subscript F) which corresponds to a zero length of commitment (Başar and Olsder, 1982; Reinganum and Stokey, 1985; van der Ploeg, 1987; Fershtman and Kamien, 1987; Reynolds, 1987; Fershtman, 1989; van der Ploeg and de Zeeuw, 1990). The solution is now obtained with the aid of Bellman's dynamic programming rather than Pontryagin's maximum principle. This ensures that if there is a shock leading to a deviation from the equilibrium path, the feedback rules for the levels of production are at later dates still optimal to carry out if called upon to do so. The policies of the open-loop Nash equilibrium are rational to carry out if called upon to do so at a later date, only as long as there are no deviations from the equilibrium path. In other words, the open-loop Nash equilibrium is time-consistent but not subgame-perfect. In order to obtain analytical results, attention is focussed on the case of quadratic net social benefits and social damage functions.

Let $V_i(S, t)$ denote the value function of country i, i.e., the equilibrium maximal value of the discounted stream of net social benefits minus social damage, from time t onwards. Then the Hamilton—Jacobi—Bellman equation for country i can be written as follows:

$$rV_i(S,t) - [\partial V_i(S,t)/\partial t] = \max_{Y_i} \left\{ \beta Y_i - \frac{1}{2} Y_i^2 - \frac{1}{2}\gamma S^2 + [\partial V_i(S,t)/\partial S]\,[(\alpha/N)\left(\sum_{j=1}^{N} Y_j\right) - \delta S] \right\}. \tag{6.1}$$

This yields

$$Y_i(S, t) = \phi(-(\alpha/N)[\partial V_i(S, t)/\partial S]) \\ = \beta + (\alpha/N)[\partial V_i(S, t)/\partial S]. \tag{6.2}$$

Upon postulating a functional form for the value function, $V_i(S, t) = \sigma_{0t} - \sigma_{1i}S - \frac{1}{2}\sigma_{2t}S^2$, substituting this and (6.2) into (6.1), imposing symmetry and equating coefficients on S and S^2, one obtains the following differential equations:

$$\dot{\sigma}_1 = (r + \delta)\sigma_1 - (\alpha\beta)\sigma_2 + \alpha^2 \left(\frac{2N - 1}{N^2}\right) \sigma_1\sigma_2 \tag{6.3}$$

$$\dot{\sigma}_2 = (r + 2\delta)\sigma_2 + \alpha^2 \left(\frac{2N - 1}{N^2}\right) \sigma_2^2 - \gamma. \tag{6.4}$$

The stationary solution for σ_1 and σ_2, associated with a concave value function ($\sigma_{2i} > 0$), is unstable, so that the transient solution for σ_1 and σ_2 must always equal the stationary solution:

$$\sigma_1 = \left(\frac{\alpha\beta\sigma_2}{r + \delta + \alpha^2 \left(\frac{2N - 1}{N^2}\right) \sigma_2}\right) > 0 \tag{6.5}$$

$$\sigma_2 = \left(\frac{-(r + 2\delta) + \left[(r + 2\delta)^2 + 4\gamma\alpha^2 \left(\frac{2N - 1}{N^2}\right)\right]^{\frac{1}{2}}}{2\alpha^2 \left(\frac{2N - 1}{N^2}\right)}\right) > 0. \tag{6.6}$$

The optimal emission charges are

$$\tau_F = -[\partial V_i(S, t)/\partial S] = \sigma_1 + \sigma_2 S, \tag{6.7}$$

so that the development of the concentration level of the pollutants is given by

$$\dot{S}_F = \left[\alpha\beta - \alpha^2 \left(\frac{\sigma_1}{N}\right)\right] - \left[\delta + \alpha^2 \left(\frac{\sigma_2}{N}\right)\right] S_F,\ S_F(0) = S_0. \tag{6.8}$$

Equation (6.8) is stable and yields the steady-state outcome:

$$S_F(\infty) = \left(\frac{\alpha\beta - \alpha^2(\sigma_1/N)}{\delta + \alpha^2(\sigma_2/N)}\right). \tag{6.9}$$

Comparing this outcome with the steady-state outcome for open-loop information patterns and pre-commitment, derived in Section 5, the following result is obtained.

PROPOSITION 6.1. *$S_I(\infty) < S_N(\infty) < S_F(\infty) < S_M(\infty)$ and $\tau_I(\infty) > \tau_N(\infty) > \tau_F(\infty) > \tau_M = 0$ hold.*

Proof. The first inequalities already appeared in (5.3) and the third inequalities are, given that σ_1, $\sigma_2 > 0$, obvious. Consider now the second inequality for the concentration levels of pollutants. Since

$$\alpha\beta - \alpha^2(\sigma_1/N) = \alpha\beta \left(\frac{r + \delta + \alpha^2 \left(\frac{N-1}{N^2} \right) \sigma_2}{r + \delta + \alpha^2 \left(\frac{2N-1}{N^2} \right) \sigma_2} \right) \tag{6.10}$$

holds, one has using (5.3) and (6.9) to prove that,

$$\left(\frac{r + \delta + \alpha^2 \left(\frac{2N-1}{N^2} \right) \sigma_2}{\delta + \left(\frac{\alpha^2 \gamma}{N(r+\delta)} \right)} \right) < \left(\frac{r + \delta + \alpha^2 \left(\frac{N-1}{N^2} \right) \sigma_2}{\delta + \alpha^2(\sigma_2/N)} \right) \tag{6.11}$$

or

$$(r + 2\delta)\sigma_2 + \alpha^2 \left(\frac{2N-1}{N^2} \right) \sigma_2^2 - \gamma < \left(\frac{\alpha^2 \gamma}{r+\delta} \right) \left(\frac{N-1}{N^2} \right) \sigma_2. \tag{6.12}$$

This last inequality is immediately clear from $\sigma_2 > 0$ and from the fact that the right-hand side of (6.4) has to be zero, because then the left-hand side of (6.12) is zero whilst the right-hand side of (6.12) is strictly positive. The second inequality for the optimal emission charges then follows immediately from $\phi' < 0$. □

The open-loop Nash equilibrium underestimates the damage of not coordinating emission charges for the environment, because the feedback Nash equilibrium is the relevant equilibrium to look at and leads to greater pollution of the environment than the open-loop Nash equilibrium. The appropriate non-cooperative equilibrium seems the subgame-perfect equilibrium, which yields more pollution than the open-loop equilibrium and *a fortiori* more than the cooperative equilibrium but less pollution than the market outcome. The intuition is as follows. An individual country that is considering to produce a marginal amount more causes an increase in the concentration level of pollutants for all countries concerned. In the feedback Nash equilibrium this country knows that the other countries will respond with somewhat higher emission charges, lower production levels and thus less pollution. This means that the marginal damage caused to the environment of an additional unit of production is less than it would be in the open-loop Nash equilibrium, so that in equilibrium the incentive to have more production and pollution will be higher in the feedback Nash than in the open-loop Nash equilibrium. The appropriate Pigouvian tax scheme for this case of feedback information patterns and a zero length of commitment is to set an emission charge of τ_F per unit of pollution. Emission charges are lower than in the open-loop case, so there is more pollution.

An important conclusion is thus that using the less realistic open-loop Nash equilibrium concept would lead one to underestimate the damage to the environment of not coordinating emission charges ($S_N(\infty) - S_I(\infty) < S_F(\infty) - S_I(\infty)$). Clearly, the more appropriate use of the feedback Nash equilibrium concept strengthens the case for international coordination of pollution control.

7. Efforts to Clean up the Environment

Countries can engage in efforts to clean up the environment. This yields an additional externality, because cleaning up rubbish is a public good as all countries benefit from it. The problem for the government of country i is then to choose $\{Y_i(t), J_i(t), t \geqslant 0\}$, where J_i denotes the efforts of country i in cleaning up the environment, in order to maximise its welfare function,

$$W_i \equiv \int_0^\infty \exp(-rt)\,[B(Y_i) - C(J_i) - D(S)]\,\mathrm{d}t, \tag{7.1}$$

where $C(J_i)$, $C' > 0$, $C'' > 0$, denotes a convex cost function, subject to the equation of the development of the concentration level of pollutants,

$$\dot{S} = (\alpha/N)\left(\sum_{i=1}^{N} Y_i\right) - \delta S - (1/N)\left(\sum_{i=1}^{N} J_i\right), \quad S(0) = S_0. \tag{7.2}$$

The market outcome is unaffected, because private agents do not find it optimal to engage in abatement activities. The outcome under international coordination of environmental policies yields, besides (4.1) and (4.2),

$$C'(J_I(t)) = (1/N)\tau_I(t) \tag{7.3}$$

which says that the marginal cost of cleaning up one unit of rubbish equals the marginal social benefit of this activity. The development of the concentration level of pollutants and the emission charge is thus described by:

$$\dot{S}_I = \alpha\phi(\alpha\tau_I/N) - \delta S_I - \psi(\tau_I/N), \quad S_I(0) = S_0 \tag{7.4}$$

and (4.4), where $\psi' = 1/C'' > 0$.

The best outcome, i.e., the outcome under international coordination of environmental policies can not be sustained by the market alone, i.e., by levying emission charges equal to τ_I, because at the same time governments must intervene and spend resources in cleaning up the environment to the level J_I. Alternatively, when individual governments levy an emission charge of τ_I and give a subsidy of (τ_I/N) per unit of private investment in cleaning up the environment, the market is forced to behave in a socially optimal way. The reason is that when individual private agents in country i choose $\{Y_i, J_i\}$ to maximise net profits, $B(Y_i) - C(J_i) - \tau_I P(Y_i) + (\tau_I/N)J_i$, they behave in a way that leads to the same outcome as under international policy coordination.

The non-cooperative (open-loop Nash) equilibrium is given by (5.2) and

$$\dot{S}_N = \alpha\phi(\alpha\tau_N/N) - \delta S_N - \psi(\tau_N/N), \quad S_N(0) = S_0. \tag{7.5}$$

The explicit steady-state solution for a quadratic net social benefits function, a quadratic social damage function and a quadratic cost function, say $C(J) = \frac{1}{2}\theta J^2$, leads to the following modification of (5.3):

$$S_I(\infty) = \left(\frac{\alpha\beta}{\delta + \left[\alpha^2 + \left(\frac{1}{\theta}\right)\right]\left(\frac{\gamma}{r+\delta}\right)} \right) <$$

$$S_N(\infty) = \left(\frac{\alpha\beta}{\delta + \left[\alpha^2 + \left(\frac{1}{\theta}\right)\right]\left(\frac{\gamma}{N(r+\delta)}\right)} \right) <$$

$$S_M(\infty) = \frac{\alpha\beta}{\delta} \tag{7.6}$$

where θ denotes the cost-of-adjustment parameter.

The feedback Nash equilibrium is given by (6.2),

$$J_i(S, t) = \psi(-(1/N)\,[\partial V_i(S, t)/\partial S]) = -(1/N\theta)\,[\partial V_i(S, t)/\partial S] \tag{7.7}$$

and (6.5)—(6.9) with α^2 replaced by $(\alpha^2 + (1/\theta))$. Proposition 6.1 still holds, so that $S_I(\infty) < S_N(\infty) < S_F(\infty) < S_M(\infty)$ and $\tau_I(\infty) > \tau_N(\infty) > \tau_F(\infty) > \tau_M = 0$. Furthermore, efforts to clean up the environment do not occur in the market outcome, are the lowest for the non-cooperative subgame-perfect outcome and the highest for the cooperative outcome ($J_I(\infty) > J_N(\infty) >$

$J_F(\infty) > J_M(\infty) = 0$). This follows immediately from (7.3). Hence, the subgame-perfect outcome leads to less cleaning-up activities than the open-loop outcome. Finally, it follows as before that the level of production is highest in the market outcome and lowest under international policy coordination and the open-loop Nash equilibrium underestimates the level of production and pollution and the potential gains from coordination ($Y_M(\infty) > Y_F(\infty) > Y_N(\infty) > Y_I(\infty)$).

The possibility of cleaning up the environment, even at a cost, leads to lower concentration levels of pollutants for the cooperative and the non-cooperative outcomes, which is not very surprising of course. It will be interesting to analyse the trade-off between investment in cleaning up, investment in clean technology and more production (see Section 8).

8. Investment in Clean Technology: Optimists versus Pessimists

The previous section analysed the potential benefits of cleaning up the stock of pollutants. Although this describes an important feature of environmental problems and is relatively straightforward to analyse, it is probably more satisfactory to assume that cleaning activities affect the rate at which pollutants are dissolved and to allow for investment in new, cleaner technology. These efforts will leave less resources available for private consumption. The disadvantage of this more realistic approach is that the non-cooperative, subgame-perfect outcome is difficult to calculate. Hence, attention will be focussed on comparing the market outcome (M) with the outcome under international policy coordination (I) and with the non-cooperative, precommitment outcome (N). The crucial question is whether one should side with the optimists or the pessimists in the environmental debate.[6] The pessimists argue that the only way to safe-guard the environment is to cut production, whilst the optimists argue that the best policy is to increase production because then more resources are available for investment in clean technology and improving the rate of degradation. This section attempts to shed some light on this important policy issue.

By investing in the stock of clean technology, say K, a country can reduce the emission-output ratio $\alpha(K)$, $\alpha' < 0$, $\alpha'' \geqslant 0$. Clean technology is assumed to be public knowledge, so that all countries benefit from the investment I_i in clean technology of an individual country i:

$$\dot{K} = \left(\sum_{i=1}^{N} I_i \right) - \rho K, \quad K(0) = K_0 \tag{8.1}$$

where $\rho \geqslant 0$ denotes the rate of depreciation of the common stock of clean technology. There are convex adjustment costs associated with investment in clean technology, say $A(I_i)$, $A(0) = A'(0) = 0$, $A'' > 0$, where $A(I_i)$ denotes the cost-of-adjustment function. It is then not possible to instantaneously change the stock of clean technology. Individual countries can also spend effort, say J_i, on reducing the prevailing depreciation rate of the concentration level of pollutants, so that instead of (3.1) one has:

$$\dot{S} = (\alpha(K)/N)\left(\sum_{i=1}^{N} Y_i\right) - \delta\left(\sum_{i=1}^{N} J_i\right) S, \quad S(0) = S_0 \tag{8.2}$$

where $\delta' > 0$. There are diminishing returns to cleaning up the environment, so that $\delta'' < 0$. Since the amount left over from total production for consumption purposes in country i equals $C_i \equiv (Y_i - I_i - A(I_i) - J_i)$, the welfare function of country i can be written as

$$W_i \equiv \int_0^{\infty} \exp(-rt)\,[B(Y_i(t) - I_i(t) - A(I_i(t)) - - J_i(t)) - D(S(t))]\,\mathrm{d}t \tag{8.3}$$

instead of (7.1). The government of country i now chooses $\{Y_i(t), I_i(t), J_i(t), t \geqslant 0\}$ in order to maximise (8.3) subject to (8.1)—(8.2).

8.1. INTERNATIONAL POLICY COORDINATION

The market outcome is the usual glum state of affairs: the level of production is set without taking into account environmental considerations and no investment in clean technology or cleaning up the environment takes place ($Y_i = Y_M$, $I_i = 0$, $J_i = 0$). The outcome under international coordination of environmental policies yields the first-order conditions:

$$B'(Y - I - A(I) - J) = (\alpha(K)/N)\tau = \delta'(NJ)S\tau \tag{8.4}$$

$$B'(Y - I - A(I) - J)\,[1 + A'(I)] = q. \tag{8.5}$$

Equation (8.4) says that the social benefit of a marginal increase in consumption must equal the marginal damage to the environment associated with the increase in production and must also equal the marginal damage to the environment associated with the reduction in cleaning-up activities. Equation (8.5) says that the marginal benefits from one unit less of investment in clean technology should equal the shadowprice of clean technology, q. In addition, the user cost of the stock of clean technology (rental charge plus depreciation charge minus capital gains) must equal the marginal benefit of an extra unit of capital stock required for cutting the emission-output ratio:

$$[r + \rho - (\dot{q}/q)]q = -\tau\alpha'(K)Y. \tag{8.6}$$

Similarly, the user cost of the stock of pollutants must equal the marginal social damage:

$$[r + \delta(NJ) - (\dot{\tau}/\tau)]\tau = ND'(S). \tag{8.7}$$

In order to perform the comparative statics of the steady state, it is for simplicity assumed that there are no cleaning-up activities ($J_i = 0$) and that the stock of clean technology does not depreciate ($\rho = 0$) so that from (8.1) the steady-state levels of investment in clean technology are zero ($I_t = 0$). It follows that the levels of consumption equal the levels of production ($C_i = Y_t$). Combining the first equality of (8.4) with (8.5) and the steady state of (8.6), one obtains the following long-run relationship:

$$C = Y = -r\left(\frac{a(K)}{a'(K)}\right) \Big/ N = \left(\frac{r}{\omega N}\right) K \tag{8.8}$$

where an iso-elastic function for the relationship between the emission-output ratio and the stock of clean technology has been assumed, i.e., $a(K) = a_0 K^{-\omega}$, $\omega > 0$. It is assumed that $\omega \leqslant \frac{1}{2}$ holds. In other words, the levels of production and consumption are proportional to the stock of clean technology. For a given stock of clean technology, the higher the efficiency of the stock of clean technology, ω, and the lower the rate of time preference, the lower the levels of consumption and production. Combining (8.2), the first equality of (8.4) and (8.7) one obtains with $D(S) = \frac{1}{2}\gamma S^2$:

$$(r + \delta)\left(\frac{B'(Y)}{a(K)}\right) = \gamma a(K) Y/\delta. \tag{8.9}$$

Substitution of (8.8) into (8.9) yields with $B(Y) = \beta Y - \frac{1}{2}Y^2$:

$$(r + \delta)\delta(\beta\omega N - rK_I) = r\gamma a_0^2 K_I^{1-2\omega}. \tag{8.10}$$

The left-hand side (LHS) and right-hand side (RHS) of (8.10) are portrayed in Figure 3. One sees that an increase in the efficiency of clean technology, $\omega' > \omega$, gives rises to an increase in the stock of clean technology, that is $\partial K/\partial\omega > 0$.[7] Whether consumption and output increase or diminish depends on the elasticity of the emission-output ratio with respect to the stock of clean technology, ω. If the elasticity ω is large, then the first term in $\partial C/\partial\omega = -(rK/N\omega^2) + (r/\omega N)(\partial K/\partial\omega)$ may be outweighed by the second term and consequently an improvement in the efficiency of clean technology boosts consumption and production. This is presumably the mechanism to which the optimists in the environmental debate refer to. However, if this elasticity is very small, an increase in efficiency is likely to reduce consumption and production. This is presumably the mechanism to which the pessimists in the environmental debate refer to.

If $\omega = \frac{1}{2}$, then (8.10) shows that

$$K_I = \left(\frac{\beta N}{2r}\right) - \left(\frac{\gamma a_0^2}{(r + \delta)\delta}\right)$$

and thus that

$$C_I = Y_I = \beta - \left(\frac{2r\gamma\alpha_0^2}{N(r+\delta)\delta} \right) < \beta.$$

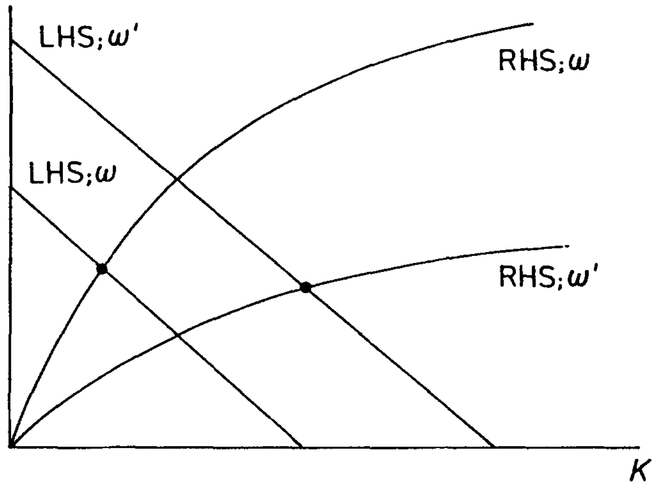

Fig. 3. Higher efficiency of the stock of clean technology.

Also, one can easily demonstrate that

$$\frac{\partial C_I}{\partial \omega} = \left(\frac{4r}{N} \right) \left(\frac{\gamma\alpha_0^2}{(r+\delta)\delta} \right) [1 + \log(K_I)] > 0$$

evaluated at $\omega = \frac{1}{2}$, because at an optimum $K_I > 1$ (else $\alpha(K_I) > \alpha_0$ and one would be better off without investing in clean technology). This means that when the elasticity of the emission-output ratio with respect to the stock of clean technology is large, one ends up being an optimist in the environmental debate. However, it is also easy to show that as $\omega \to 0$ one has $(\partial C_I / \partial \omega) \to -\infty$, even though $(\partial K_I / \partial \omega) > 0$, so that for low values of ω one ends up being a pessimist. In fact, with the aid of the mean-value theorem one can estabilish an U-shaped relationship between private consumption and output levels on the one hand and the elasticity of the emission-output ratio with respect to the stock of clean technology on the other hand. The point, where the U-shaped curve cuts the vertical axis, of course, corresponds to the equilibrium without investment in clean technology, as discussed in Section 4.

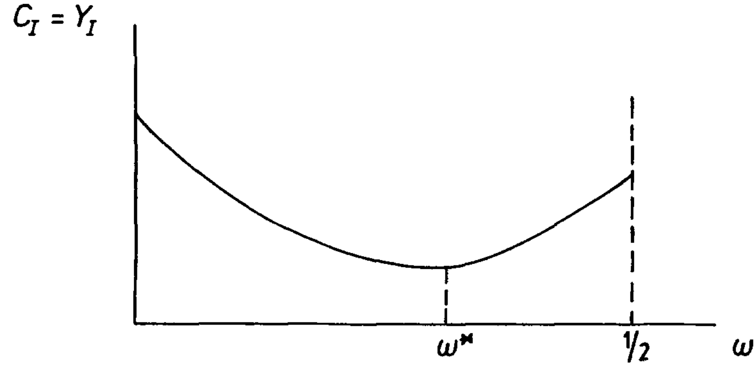

Fig. 4. Optimists and pessimists in the environmental debate.

8.2. INTERNATIONAL STALEMATES IN POLLUTION CONTROL

In the absence of international policy coordination, the open-loop Nash outcome yields (8.4), (8.5), (8.6) and, instead of (8.7),

$$[r + \delta(NJ) - (\dot{\tau}/\tau)]\tau = D'(S). \tag{8.11}$$

Hence, the marginal social damage taken account of by each of the countries is N times less as under international policy coordination because the adverse effects of more pollution on other countries are not internalised. The equivalent long-run relationship to (8.10) for non-cooperative policy making is given by:

$$(r + \delta)\delta N(\beta\omega N - rK_N) = r\gamma a_0^2 K_N^{1-2\omega}. \tag{8.12}$$

For example, if $\omega = \frac{1}{2}$, then

$$K_N = \left(\frac{\beta N}{2}\right) - \left(\frac{\gamma a_0^2}{(r + \delta)\delta N}\right) > K_I$$

and

$$Y_M = \beta > Y_N = \beta - \left(\frac{2r\gamma a_0^2}{N^2(r + \delta)\delta}\right) > Y_I.$$

This is perhaps a somewhat counter-intuitive result, but arises because the marginal benefit of consumption and production should equal the marginal benefit to the environment of an additional unit of investment in clean technology (cf., expression (8.9)). Hence, absence of international coordination of pollution control leads to too high levels of production and consumption but also to too excessive levels of stocks of clean technology. Figure 5 suggests that this result is fairly general. It is crucial to know what happens to the concentration level of pollutants. Competitive decision making can increase or decrease this level depending on whether the increase in production or the increase in clean technology dominates. In the former case one believes that absence of international policy coordination causes primarily increases in production, consumption and pollution and rather less increases in clean technology, so one belongs in the camp of the pessimists. In the latter case one believes that there is enough scope for clean technology to counter-act the adverse effects of production on pollution, so that one belongs in the camp of the optimists. For the special case $\omega = \frac{1}{2}$, it is easy to show that international coordination of pollution control leads to a lower concentration level of pollutants ($S_I < S_N$), giving in this case some support to the pessimists. Hence, if $\omega = \frac{1}{2}$, international coordination leads to lower levels of production, consumption, clean technology and pollutants.

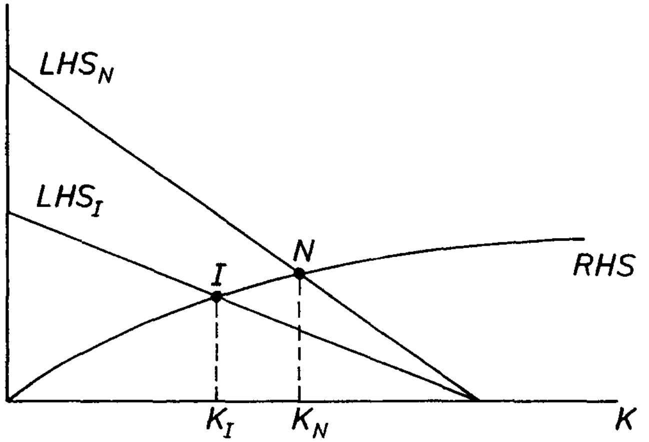

Fig. 5. International coordination of investment in clean technology.

9. Concluding Remarks

It has been established that when the market is left to its own devices there will be too much production and too much pollution, because effectively no price is charged for the right to damage the environment. When individual governments do charge a price by levying emission charges, production and pollution fall and the environment improves. When individual governments coordinate the setting of emission charges, these charges will be higher and lead to even lower levels of production and pollution. As far as the non-cooperative outcome is concerned, it is important to use the subgame-perfect or feedback Nash equilibrium rather than the open-loop Nash equilibrium, because otherwise the optimal emission charges will be overestimated and the levels of production and pollution will be too low. The point is that the feedback Nash equilibrium is the appropriate equilibrium to use from a theoretical point of view, and that it leads in the absence of international policy cooperation to lower emission charges and more pollution than the open-loop Nash equilibrium. When one allows for efforts to clean up the environment, one finds that less of this occurs in the subgame-perfect, non-cooperative outcome than in the open-loop, non-cooperative outcome and *a fortiori* less than in the cooperative outcome. When one allows for investment in clean technology and efforts to arrest the degradation of the environment, it is possible that the adverse effects of excessive levels of production on the environment which occur when there is no international coordination of pollution control are outweighed by the beneficial effects of excessive levels of investment in clean technology on the environment. In that case, one may side with the optimists rather than the pessimists in the environmental debate.

Future research will be concerned with the environmental aspects of the Ramsey problem (e.g., Blanchard and Fischer, 1989, Chapter 2) and allows one to investigate in what way environmental considerations lead the economy away from the golden rule. Although much work in this area has already been done (e.g., Keeler *et al.*, 1971), not much has been done within an international context. It is also of interest to analyse the effects of population growth, because this has a beneficial effect on economic growth but a detrimental effect on the environment. Future research will also be concerned with multi-country models of environmental control with an explicit treatment of two sectors, one production sector and one abatement sector (cf., Siebert, 1987; Musu, 1989).

Appendix: More Pollution at Home than Abroad

This Appendix shows that when it is assumed that production at home pollutes the environment more at home than abroad, the steady-state results do not change. Hence, the model in Section 3 is extended to allow for separate pollution levels in each country, S_i, $i = 1, \ldots, N$. It is assumed that a fraction π of the emission remains at home, whereas the rest of the emission spreads out to the other countries, hence (3.1) becomes

$$\dot{S}_i = \pi a Y_i + \left(\frac{(1-\pi)a}{N-1}\right)\left(\sum_{j=1, j\neq i}^{N} Y_j\right) - \delta S_i,$$

$$S_i(0) = S_{i0}, \quad i = 1, \ldots, N. \tag{3.1'}$$

When one defines the global concentration level of pollutants as $S \equiv (\Sigma_{i=1}^{N}$

$S_i)/N$, one obtains (3.1) by adding up. The welfare function of government i is now given by

$$W_i \equiv \int_0^\infty \exp(-rt)\,[B(Y_i(t)) - D(S_i(t))]\,\mathrm{d}t. \tag{3.2'}$$

It is clear from considerations of symmetry that the steady-state results will not change. A more formal analysis of the open-loop case yields for each country shadow prices for the pollution levels of the other countries. These shadow prices tend to zero in the long run. A more formal analysis of the feedback case requires value functions of the form $V_i(S_i, t) = \sigma_{0i} - \sigma_{1i}S_i - \frac{1}{2}\sigma_{2i}S_i^2$ for country i, $i = 1, \ldots, N$, which do not depend on S_j, $j \neq i$. From there the steps in Section 6 are unaltered. Hence, allowing for more pollution at home than abroad does not change the steady-state results.

However, a much more interesting issue to look at is asymmetries in emissions. The problem of "down-stream" pollution is, of course, a classic one. For example, the pollution associated with industrial production in the Ruhr area of West Germany (country 2) is dumped in the Rhine and poses serious environmental problems down-stream in the Netherlands (country 1). Another example is the burning of fossil fuel in factories in the United Kingdom (country 2), which causes acid rain and destroys forests in Scandinavia (country 1). In the model such asymmetries are best captured, for the case $N = 2$, by allowing the fraction of the emission to remain at home to be smaller for country 2 than for country 1, $\pi_1 > \pi_2$. The extreme case is, of course, that all the pollution of country 2 ends up in country 1, say $\pi_1 = 1$, $\pi_2 = 0$, which yields

$$\dot{S}_1 = \alpha(Y_1 + Y_2) - \delta S_1, \quad S_1(0) = S_{10} \tag{3.1''}$$

and $S_2 = 0$. In a non-cooperative equilibrium outcome the up-stream country always chooses a level of output corresponding to the market outcome, $Y_2 = Y_M(= \beta)$, because its government does not bother to levy emission charges. The down-stream country simply has to accept the resulting damage to the environment. The government of country 1 will levy higher emission charges, but still ends up with more pollution than would be the case when the up-stream country did not produce. To be precise, the concentration level of pollutants and the emission charge of the down-stream country satisfy:

$$\dot{S}_{1N} = \alpha[\phi(\alpha\tau_1) + Y_M] - \delta S_{1N}, \quad S_{1N}(0) = S_{10}$$
$$\dot{\tau}_{1N} = (r + \delta)\tau_{1N} - D'(S_{1N}).$$

For the quadratic specification, both the steady-state emission charge and pollution level are double what they would be when there is no rubbish from up-stream:

$$\tau_{1N}(\infty) = \left(\frac{2\alpha\beta\gamma}{\alpha^2\gamma + \delta(r + \delta)}\right), \quad \tau_{2N} = 0 \quad \text{and}$$

$$S_{1N}(\infty) = \left(\frac{2\alpha\beta}{\delta + \left(\frac{\alpha^2\gamma}{r + \delta}\right)}\right).$$

Now consider a benevolent planner who chooses the optimal emission charges in both the up-stream and the down-stream country to maximise global welfare. Apart from the usual conditions, the planner takes care to equalise the marginal benefit of production in each of the two countries and to set them equal to the marginal loss in welfare of an additional unit of production, $B'(Y_1) = B'(Y_2) = \alpha\tau_I$. The development of the optimal concentration level of pollutants down-stream and the cooperative emission charge satisfy:

$$\dot{S}_{1I} = 2\alpha\phi(\alpha\tau_I) - \delta S_{1I},\ S_{1I}(0) = S_{10}$$

$$\dot{\tau}_I = (r + \delta)\tau_I - D'(S_{1I}).$$

For the quadratic specification, one obtains

$$\tau_{2N} = 0 < \tau_I(\infty) = \left(\frac{2\alpha\beta\gamma}{2\alpha^2\gamma + \delta(r + \delta)}\right) < \tau_{1N}(\infty) \text{ and}$$

$$S_{1I}(\infty) = \left(\frac{2\alpha\beta}{\delta + 2\left(\frac{\alpha^2\gamma}{r + \delta}\right)}\right) < S_{1N}(\infty).$$

Hence, the benevolent planner levies the same emission charge on both countries, the up-stream country is obviously worse off and the down-stream country, whose producers now face a lower emission charge, is better off. The welfare gain of the down-stream country exceeds the welfare loss of the up-stream country. The down-stream country must make side-payments, and finds it optimal to do, in order to induce the up-stream government to levy the right amount of emission charges (e.g., Mäler, 1989b).

Notes

[1] Most of the previous literature on international aspects of environmental problems (e.g., Mäler, 1989a, b; van Ierland, 1990; Krutilla, 1990; Hoel, 1990a, 1991) does not consider explicitly the dynamics of the concentration level of pollutants and does not use the framework of differential games. However, other work does seem explicitly concerned with such dynamic issues as well (Hoel, 1990b). Important recent work on the dynamic games associated with the tragedy of the commons may be found in Dutta and Sundaram (1989) and in Benhabib and Radner (1989).

[2] For an overview of models with optimal capital accumulation and pollution control, see Tahvonen and Kuluuvainen (1990) and van der Ploeg and Withagen (1991). The classic reference is Keeler, Spence and Zeckhauser (1971).

[3] The model in this section is based on Chapter 8 of Dasgupta (1982) and extends it to allow for multiple countries.

[4] Within the context of the optimal harvesting of a common renewable resource one often finds that the prevailing use of open-loop information concepts seriously underestimates the environmental damage. With iso-elastic demand and zero extraction costs, the open-loop Nash equilibrium leads to Pareto efficient harvesting rates whilst the feedback Nash or perfect equilibrium leads to too rapid extinction of the renewable resource (van der Ploeg, 1987). Section 6 also finds that the open-loop Nash equilibrium underestimates the damage caused by pollution and leads to too low emission charges.

[5] From equation (4.1) it follows that the function $\phi(\cdot)$ is given by $\phi(x) = \beta - x$. The expressions for $S_I(\infty)$ and $S_N(\infty)$ then follow from the steady states of equations (4.3)—(4.4) and equations (5.1)—(5.2), respectively.

[6] The optimist-pessimist debate is also highly relevant in the context of environmental policy for the Single European Market (e.g., Folmer and Howe, 1991.)

[7] Mathematically, one has

$$\frac{\partial K}{\partial \omega} = \left[\frac{(r+\delta)\delta\beta N + 2r\gamma\alpha_0^2 K^{1-2\omega}\log(K)}{(r+\delta)\delta r + r\gamma\alpha_0^2(1-2\omega)K^{-2\omega}}\right] > 0.$$

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