The Implications of International Cooperation for Economic Growth, Environmental Quality and Welfare*

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Abstract

National authorities are presently not willing to install a supranational authority vested with the competencies required to internalize global environmental externalities. Therefore we adopt a dynamic framework of two economies (i.e. Europe and rest of world) and analyze their strategic interactions in the presence of international knowledge spillovers and international environmental externalities – both are empirically significant. Starting from noncooperation we investigate the effects of environmental cooperation, knowledge cooperation and full cooperation. We argue that because of international patent markets, knowledge spillovers are already internalized to a huge extent. For the output-induced pollution specification we found that the existence of international patent markets is partly responsible for the present environmental degradation. Therefore it is uncertain whether the creation of patent markets in the past – though stimulating growth – increased welfare. However, for the capital-induced pollution specification, internalizing the knowledge spillovers goes hand in hand with a better environmental quality.

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1. Introduction

The fact that many environmental problems, as for example acidification or pollution of rivers and lakes, are international rather than national in nature implies that environmental externalities will not be fully internalized by means of national tax policies. Many of the most pressing environmental problems, such as the anthropogenic greenhouse effect or the destruction of the ozone layer, even possess a global character.[1] Just by assuming a supranational authority vested with the required competencies – for example, to introduce global environmental taxes – models of closed economies could be used to analyze the effects of a global environmental policy on growth and welfare. Then the world economy could be interpreted as a closed economy. However, this assumption is unrealistic. For the time being national governments are not willing to install supranational authorities vested with the required competencies to internalize global externalities. It is thus surprising that the investigation of international or global environmental externalities are rarely analyzed in open dynamic frameworks.

In addition to international environmental spillovers there may exist other *non*-environmental transboundary externalities. In fact, empirical evidence suggests that foreign cumulative R&D is an important determinant of domestic productivity. For example, Coe and Helpman (1995) find by using pooled time-series/cross-section data of 21 OECD countries plus Israel during the period 1971-90 that foreign R&D capital stock has important effects on the total domestic factor productivity, and these are stronger the more open an economy is to foreign trade. Cumulative R&D expenditure is here used as a proxy for the stock of knowledge. The benefits from foreign R&D, for instance, consist of learning about new technologies and materials, production processes, or organizational methods. As R&D capital is a specific form of human capital associated with innovation, Engelbrecht (1997) additionally distinguishes between R&D and 'general' human capital, measured as average years of schooling of the labor force. His study supports the statistically significant results of Coe and Helpman and finds the same effects for general human capital.

The above mentioned observations lead us to study the strategic interactions between two countries (for instance Europe and the rest of world) within the framework of a differential game and to answer the question how pollution, economic growth and welfare are influenced by different international policy coordinations. Therefore we develop a model by considering international knowledge and international environmental spillovers in a framework with Uzawa–Lucas production processes. We assume that every coun-

[1] For surveys on international environmental problems, see Mäler (1990) or Sandler (1997).

try is mutually affected by negative international environmental spillovers generated by the production process and by positive international knowledge spillovers associated with the accumulation of human capital. The welfare of the representative agent in every country is negatively affected by environmental pollution of the domestic and the foreign countries, whereas the accumulation of human capital is an increasing function of the domestic human-capital stock and of foreign human-capital spillovers. Households invest in the stock of knowledge which has the character of an international public good in the absence of international patent markets. For simplicity, we assume two identical countries, implying that international trade and capital flows are absent. We derive both the noncooperative open-loop Cournot–Nash equilibrium where countries are assumed not to take into account the effects of their actions on the other country and the full cooperative outcome, corresponding to supranational planning. Starting from noncooperation we are thus able to investigate the effects of environmental cooperation, knowledge cooperation and full cooperation.

We now briefly review the literature on environmental policy in open endogenously growing economies. The analysis of environmental policy in open endogenously growing economies has been largely ignored in the literature. Exceptions are van der Ploeg and Ligthart (1994), Elbasha and Roe (1996), Bretschger (1998a) and Hettich and Svane (1998). Elbasha and Roe (1996) find for a small open endogenously growing economy where growth is driven by innovation that long-run growth rises with a country's endowment in primary factors, with the degree of openness and with the degree of market power of patent holders. Furthermore, the effects of environmental policy on growth depend on the intertemporal elasticity of substitution. In a north/south model with two different assumptions on the dislocation of firms from the north to the south Bretschger (1998) analyses the effects of a tighter environmental policy in the north. By using a model where growth is endogenously driven by innovation he shows that although pollution may rise in the south, the global environmental quality improves. However, the positive environmental effect is accompanied by a lower economic growth rate. Hettich and Svane (1998) show that the possibilities of a small open economy to pursue an independent environmental policy depend upon the tax system. Under a residence-based income tax system which discriminates between domestic source and foreign source income it is possible to pursue an independent environmental policy thereby determining the own growth rate. Under a source-based tax system, where the after-tax interest rate should equal the world interest rate, the government can no longer pursue an own first best environmental policy since the interest rate is given.

This present paper was inspired by the contribution of van der Ploeg and Ligthart (1994). They analyze the strategic interaction between two identical countries in an endogenous growth model and take into account three international spillovers: knowledge spillovers, externalities resulting from government spending on a productive public good and environmental externalities. In their one-sector growth model growth is driven by infrastructure.[2] To a certain degree we adopt their approach, however we assume a different production technology. Using the two-sector Uzawa–Lucas model – with a separate education sector – allows us to distinguish explicitly between human capital and physical capital and thus provides a better possibility for modeling knowledge spillovers. We shall see that allowing for substitution between physical and human capital in the production process changes the effects of cooperation substantially. Furthermore, in contrast to their contribution, we shall see that certain results of cooperation depend on whether physical capital or final good production is responsible for pollution.

The results of the paper are the following: We argue that because of international patent markets, knowledge spillovers are already internalized to a huge extent, i.e. knowledge cooperation describes best the real world in our model. For the output-induced pollution specification we find that the existence of international patent markets is partly responsible for the present environmental degradation. Therefore it is uncertain whether the creation of patent markets in the past – though stimulating growth – increases welfare. However, for the capital-induced pollution specification, internalizing the knowledge spillovers goes hand in hand with a better environmental quality. Independent of the pollution specification we find that a pollution cooperation lowers environmental degradation, increases welfare while leaving the growth rate unaffected.

In the following, we first describe in Section 2 the setup for the two-country economy. As the effects of cooperation depend on the pollution specification, in Section 3 we choose physical capital as the polluting factor and in Section 4 final output as the polluting factor. In order to determine the cooperation effects, we derive in both sections the noncooperative open-loop Cournot–Nash equilibrium and the cooperative outcome which would result under supranational planning. By comparing the reduced forms we can assess the effects of cooperation on growth, pollution and welfare. Section 5 summarizes the results and concludes.

2. The Analytical Framework

We analyze the strategic interactions between two countries. Every country is mutually affected by positive international knowledge spillovers associated with human capital accu-

[2] It is a Barro type of model, that is, with a productive public good.

mulation and negative international environmental spillovers generated by the production process. We derive both the noncooperative open-loop Cournot–Nash equilibrium where countries are assumed not to take into account the effects of their actions on the other country and the full cooperative outcome, corresponding to supranational planning i.e. a global first-best solution. We are thus able to analyze the effects of knowledge cooperation, pollution cooperation and full cooperation. The open-loop Nash solution assumes that players have only initial state information and that the period of commitment is equal to the entire planning horizon. Every country is represented by a national benevolent central planner. Therefore, countries are treated as unit actors and the internal national decision-making process is ignored.

The underlying assumptions imply that important aspects of international environmental cooperations are ignored. Assuming that the period of commitment is equal to the entire planning horizon implies that stability problems are ruled out. Since we consider only two countries, cooperative equilibria with only a subgroup of countries participating are not possible either.[3] Finally, due to the assumption of identical countries all environmental agreements are cost efficient.[4] Nevertheless, we analyze not only the noncooperative and the full cooperative solutions, but also partial environmental or knowledge cooperations.

We consider a global economy consisting of two identical countries, the home country and the foreign country, the latter being indicated by an asterisk '$*$'. Every economy is described by a two sector endogenous growth model. The production structure is based on the Uzawa–Lucas model extended by an international human capital spillover and an international environmental externality. The first sector produces a perfect malleable output good while in the second sector human capital is accumulated. Since the countries are identical, we in the following describe the economy only from the domestic perspective.

In the first sector, the final good Y is produced with a Cobb–Douglas technology that possesses constant returns to scale with respect to physical capital K and effective labor (uH) but diminishing returns to factors separately:

$$Y_t = A\ K_t^{\alpha}\left(u_t H_t\right)^{1-\alpha}, \tag{2.1}$$

where $A, H, K, Y > 0, 0 < \alpha < 1$ and $0 \leqslant u \leqslant 1$. Effective labor is defined as the

[3] See, for example, Barrett (1994) for the issues of stability and coalition size of international environmental agreements in static and dynamic games of identical countries. For agreements of subcoalitions including side payments between identical countries, see Carraro and Siniscalco (1993), and between heterogeneous countries, see Petrakis and Xepapadeas (1996).

[4] For the problems of cost-effectiveness in international environmental agreements, see Hoel (1993) and Schmidt (2000) in static, and Kverndokk (1993) in dynamic frameworks.

product of u – the fraction of the unit time budget that is devoted to production of the final good – and human capital H. Parameters α and $1-\alpha$ are the exogenous shares of physical capital and effective labor, respectively, and A reflects the exogenously given level of the technology. Both inputs H and K can be accumulated infinitively. Therefore, falling marginal products to one factor can be avoided and unlimited growth is in principle possible. The flow resource constraint of the economy is given by:[5]

$$Y_t = C_t + \dot{K}_t + Z_t + \delta_K K_t. \tag{2.2}$$

where $C, Z, \delta_K \geqslant 0$. Final output Y can be used either for consumption C, for net investment in the physical capital stock $\dot{K}$, for private abatement activities Z, or to prevent the current physical capital stock from depreciation $\delta_K K$.

In the education sector, human capital is accumulated with a constant returns to scale technology which utilizes human capital whereas physical capital is negligible:

$$\dot{H}_t = B\left[(1-u_t)\,H_t\right]^{\beta}\left[\left(1-\overset{*}{u}_t\right)\overset{*}{H}_t\right]^{(1-\beta)} - \delta_H H_t, \tag{2.3}$$

where $B, H, \delta_H \geqslant 0$. Parameter B is the studying productivity, $(1-u)$ is the fraction of the unit time budget devoted to education $(0 \leqslant u \leqslant 1)$, δ_H is the depreciation rate of human capital and $0 < \beta < 1$ is the exogenous domestic human capital share in education. New human capital is accumulated by using time and old human capital. However, it is produced not only by using domestic human capital (first bracket on the rhs) but also by using foreign human capital (second bracket on the rhs), which is indicated by an asterisk '$*$'. The latter is exogenous for the home country and reflects the international human capital spillover.

The utility function of the domestic country depends on the trade-off between consumption and pollution. The corresponding lifetime utility is given by

$$U_0 = \int\limits_{t=0}^{\infty} \frac{\left(C_t P_t^{-\eta_P}\right)^{(1-1/\varepsilon)} - 1}{1-1/\varepsilon} e^{-\rho t}dt, \quad \text{for} \quad \varepsilon > 0, \varepsilon \neq 1 \tag{2.4}$$

$$U_0 = \int\limits_{t=0}^{\infty} \ln C - \eta_P P, \quad \text{for} \quad \varepsilon = 1. \tag{2.5}$$

Utility is seen to be increasing in consumption at a decreasing rate, $U_C > 0, U_{CC} < 0$, while it is decreasing in aggregate pollution $U_P < 0$. Utility is decreasing in aggregate

[5] A variable with a dot denotes the derivative with respect to time while a variable with a hat stands for its growth rate.

pollution at an increasing rate $U_{PP} > 0$, at a constant rate $U_{PP} = 0$, or at a decreasing rate $U_{PP} < 0$ for ε larger than, equal to, or smaller than $\eta_P / (1 + \eta_P)$. The positive parameter η_P represents the weight of pollution in utility.[6]

Pollution generated by the home country p, and pollution caused by the foreign country $\overset{*}{p}$, contribute to total pollution P. Thus global pollution is a weighted sum of national and foreign pollution:

$$P_t = p_t + (1 - \eta_F)\, \overset{*}{p}_t, \tag{2.6}$$

where $0 \leq \eta_F \leq 1$. By means of parameter η_F we can distinguish different kinds of externalities. In the case of a global externality such as the anthropogenic greenhouse effect it does not matter where pollution is generated and total pollution is the sum of national and foreign pollutions ($P = p + \overset{*}{p}$), obtained by setting parameter $\eta_F = 0$. However, in the case of acid rain, transboundary pollution depends on the strength and direction of the wind. In the model this can be illustrated by setting η_F somewhere between zero and unity. Finally, setting $\eta_F = 1$ reflects the case of a pure national externality such as noise or smog.

We analyze two plausible pollution specifications: Pollution is either generated by the use of physical capital in production or by production itself as a side product. The externality is assumed to affect individuals' utility negatively, but does not harm the production process, that is, there are no positive spillovers of a better environment to the production of goods. Following the literature, pollution p can be reduced by means of abatement activities Z, which in turn consume a part of output, in line with the flow resource constraint (2.2). The pollution specifications are given by

$$p = \left(\frac{K}{Z}\right)^{\chi}, \tag{2.7}$$

$$p = \left(\frac{Y}{Z}\right)^{\chi}, \tag{2.8}$$

where χ is the exogenous elasticity of P with respect to ratios K/Z or Y/Z. Thus, given a certain stock of physical capital or a certain level of output, pollution can be reduced by raising the level of abatement activities.

3. Physical Capital as the Polluting Factor

In this section we assume that pollution is caused by using physical capital in production and can be reduced by abatement activities, see eq. (2.7). For this pollution specification

[6] U_0 represents the present value of the future instantaneous utility levels, and parameter ρ is the rate of time preference, which is assumed to be strictly positive.

we derive in the following the noncooperative solution, the cooperative solution and finally the cooperation effects on core variables.

3.1. The Noncooperative Solution

The strategic interactions over time between the two countries are modeled as a differential game. For the noncooperative solution the symmetrical countries are assumed to behave in a Cournot–Nash manner: given the selected plan of the foreign government the benevolent planner of the home country maximizes lifetime utility (2.4) of the representative citizen by choosing the time paths of domestic consumption, abatement activities, physical and human capital accumulation, and the fraction of time devoted to production subject to the domestic resource constraint (2.2) and the human capital accumulation constraint (2.3). Since countries are assumed to be identical, no trade will occur in equilibrium and international flows of commodities or capital can be ignored. The current-value Hamiltonian for the domestic optimization problem is given by

$$\begin{aligned} \max_{C,Z,u} \mathcal{H} &= U\left[C, P\left(p, \overset{*}{p}\right)\right] \\ &+ \lambda\left[AK^{\alpha}\left(uH\right)^{1-\alpha} - C - Z - \delta_K K\right] \\ &+ \mu\left\{B\left[\left(1-u\right)H\right]^{\beta}\left[\left(1-\overset{*}{u}\right)\overset{*}{H}\right]^{(1-\beta)} - \delta_H H\right\}. \end{aligned} \tag{3.1}$$

Note that variables $(1-\overset{*}{u})\overset{*}{H}$ and $\overset{*}{p}$ are exogenously given for the domestic country reflecting the international knowledge and pollution spillovers from the foreign country, respectively.

Analogously the current-value Hamiltonian for the foreign central planner reads

$$\begin{aligned} \max_{\overset{*}{C},\overset{*}{Z},\overset{*}{u}} \overset{*}{\mathcal{H}} &= \overset{*}{U}\left[\overset{*}{C}, \overset{*}{P}\left(\overset{*}{p}, p\right)\right] \\ &+ \overset{*}{\lambda}\left[A\overset{*}{K}^{\alpha}\left(\overset{*}{u}\overset{*}{H}\right)^{1-\alpha} - \overset{*}{C} - \overset{*}{Z} - \delta_K \overset{*}{K}\right] \\ &+ \overset{*}{\mu}\left\{B\left[\left(1-\overset{*}{u}\right)\overset{*}{H}\right]^{\beta}\left[\left(1-u\right)H\right]^{(1-\beta)} - \delta_H \overset{*}{H}\right\}. \end{aligned}$$

For the foreign central planner variables $(1-u)H$ and p are exogenously given. Since the two countries are identical it is sufficient to derive the first-order conditions for one country. Due to the assumed symmetry of the countries, the first-order conditions of the home and the foreign countries are equivalent. Thus, it is sufficient to derive the first-order conditions for one country. Furthermore, the domestic variables solving the domestic planning problem are identical to the corresponding foreign variables, hence

$$C = \overset{*}{C},\ \ H = \overset{*}{H},\ \ K = \overset{*}{K},\ \ P = \overset{*}{P},\ \ p = \overset{*}{p},\ \ u = \overset{*}{u},\ \ \mu = \overset{*}{\mu},\ \ \lambda = \overset{*}{\lambda}\,. \tag{3.2}$$

In addition, along a balanced growth path the variables C, H, K, Y Z grow at the same constant rate g, whereas u is constant over time:

$$g \equiv \hat{C} = \hat{H} = \hat{K} = \hat{Y} = \hat{Z}, \quad 0 = \dot{u}. \tag{3.3}$$

Because of condition (3.3), the ratios C/K, Z/K, K/H, Y/K and Y/Z are constant, and therefore pollution P is constant along a balanced growth path as well. A constant level of P is in accordance with sustainable development if the ecosystem is assumed to be a renewable resource and the level of pollution does not exceed the its absorbtion capacity.

Using conditions (3.2) and (3.3), the first-order conditions along a balanced growth path determine the following system of equations:

$$\frac{Z}{K} = \frac{\chi\eta_P}{2-\eta_F}\frac{C}{K}, \tag{3.4}$$

$$g = \varepsilon\left(\alpha\frac{Y}{K} - \frac{Z}{K} - \delta_K - \rho\right), \tag{3.5}$$

$$g = \varepsilon\left(\beta B - \delta_H - \rho\right), \tag{3.6}$$

$$g = \frac{Y}{K} - \frac{C}{K} - \frac{Z}{K} - \delta_K, \tag{3.7}$$

$$g = B\left(1-u\right) - \delta_H. \tag{3.8}$$

Eq. (3.4) requires that the marginal utility of consumption and abatement must be equalized. Eq. (3.5) represent the Keynes–Ramsey rule. According to it the economy grows, remains constant, or declines if the return to physical capital $\alpha\frac{Y}{K}$ corrected by the marginal damage of pollution $\frac{Z}{K}$ is larger than, equal to, or smaller than the sum of the rate of physical capital depreciation and the rate of time preference. Eq. (3.6) represents the second Euler condition. It says that the economy grows, remains constant or declines if the marginal product of human capital in the education sector βB is larger than equal to, or smaller the sum of the rate of human capital depreciation and the rate of time preference. Eq. (3.7) is the flow resource constraint of the economy and eq. (3.8) is the human capital accumulation constraint. Eq. (3.6) is already the reduced form of g. The other reduced forms of the time devoted to production u, the consumption-capital ratio $\frac{C}{K}$, the output-capital ratio $\frac{Y}{K}$ and the abatement-capital ratio $\frac{Z}{K}$ can be derived immediately by using the first-order conditions (3.4)–(3.8):

$$u = \frac{B - \varepsilon\left(\beta B - \delta_H - \rho\right) - \delta_H}{B}, \tag{3.9}$$

$$\frac{C}{K} = \frac{\left(1-\alpha\varepsilon\right)\left(\beta B - \delta_H - \rho\right) + \left(1-\alpha\right)\delta_K + \rho}{\alpha + \left(\alpha - 1\right)\frac{\eta_P \chi}{2-\eta_F}}, \tag{3.10}$$

$$\frac{Y}{K} = \frac{\left(1-\varepsilon\right)\left(\beta B - \delta_H - \rho\right) + \frac{2-\eta_F}{\chi\eta_P}\left(\beta B - \delta_H + \delta_K\right) + \rho}{\alpha - 1 + \frac{\alpha(2-\eta_F)}{\eta_P \chi}}, \tag{3.11}$$

$$\frac{Z}{K} = \frac{\left(1-\alpha\varepsilon\right)\left(\beta B - \delta_H - \rho\right) + \left(1-\alpha\right)\delta_K + \rho}{\alpha - 1 + \frac{\alpha(2-\eta_F)}{\eta_P \chi}}. \tag{3.12}$$

To identify the effects of cooperation we compare the reduced forms of the noncooperative solution with the reduced forms of the cooperative solution which we shall derive in the following.

3.2. The Cooperative Solution

In the cooperative solution each national social planner takes into account the effects of their decisions on the other country, hence all international spillovers are internalized. The easiest way to derive the global optimum is to assume a supranational social planner. A supranational planner chooses $C, Z, u, \overset{*}{C}, \overset{*}{Z}, \overset{*}{u}$ in order to maximize the sum of lifetime welfare in both countries subject to the national resource and human capital accumulation constraints. The current-value Hamiltonian for this optimization problem is given by

$$\begin{aligned} \max_{C,Z,u,\overset{*}{C},\overset{*}{Z},\overset{*}{u}} \mathcal{H} &= U\left[C, P\left(p, \overset{*}{p}\right)\right] + \overset{*}{U}\left[\overset{*}{C}, \overset{*}{P}\left(\overset{*}{p}, p\right)\right] \\ &+ \lambda\left[AK^{\alpha}\left(uH\right)^{1-\alpha} - C - Z - \delta_K K\right] \\ &+ \overset{*}{\lambda}\left[A\overset{*}{K}^{\alpha}\left(\overset{*}{u}\overset{*}{H}\right)^{1-\alpha} - \overset{*}{C} - \overset{*}{Z} - \delta_K \overset{*}{K}\right] \\ &+ \mu\left\{B\left[\left(1-u\right)H\right]^{\beta}\left[\left(1-\overset{*}{u}\right)\overset{*}{H}\right]^{(1-\beta)} - \delta_H H\right\} \\ &+ \overset{*}{\mu}\left\{B\left[\left(1-\overset{*}{u}\right)\overset{*}{H}\right]^{\beta}\left[\left(1-u\right)H\right]^{(1-\beta)} - \delta_H H\right\}. \end{aligned} \tag{3.13}$$

After eliminating the shadow prices and imposing the symmetry condition (3.2) the first-order conditions along a balanced growth path are given by

$$\frac{Z}{K} = \chi\eta_P\frac{C}{K}, \tag{3.14}$$

$$g = \varepsilon\left(\alpha\frac{Y}{K} - \frac{Z}{K} - \delta_K - \rho\right), \tag{3.15}$$

$$g = \varepsilon\left(B - \delta_H - \rho\right), \tag{3.16}$$

$$g = \frac{Y}{K} - \frac{C}{K} - \frac{Z}{K} - \delta_K, \tag{3.17}$$

$$g = B\left(1 - u\right) - \delta_H. \tag{3.18}$$

Comparing eq. (3.4) with (3.14) and (3.6) with (3.16), we see that the marginal utility of abatement and the marginal product of human capital are increased in the cooperative solution, respectively – remember that $0 \leqslant \eta_F \leqslant 1$ and $0 < \beta \leqslant 1$. This policy corresponds to a positive shock in consumers' preferences for environmental quality η_P and in the studying productivity parameter B of education sector. In the noncooperative solution the national central planner does not take into account the international environmental spillovers, that is, that domestic pollution creates a disutility in the foreign country as well. Therefore, the marginal utility of abatement is too low from a global welfare point of view. Furthermore, in the noncooperative solution the central planner does not take into account the beneficial effects of domestic human capital accumulation for the foreign country. Hence, in the noncooperative solution the return to human capital is too low from a global welfare point of view.

Eq. (3.16) is already the reduced form of the growth rate. By using eqs. (3.14)–(3.18) we can derive the reduced forms of u, C/K, Y/K K/Z:

$$u = \frac{B - \varepsilon\left(B - \delta_H - \rho\right) - \delta_H}{B}, \tag{3.19}$$

$$\frac{C}{K} = \frac{\left(1 - \alpha\varepsilon\right)\left(B - \delta_H - \rho\right) + \left(1 - \alpha\right)\delta_K + \rho}{\alpha + \left(\alpha - 1\right)\eta_P\chi}, \tag{3.20}$$

$$\frac{Y}{K} = \frac{\left(1 - \varepsilon\right)\left(B - \delta_H - \rho\right) + \frac{1}{\chi\eta_P}\left(B - \delta_H + \delta_K\right) + \rho}{\alpha - 1 + \frac{\alpha}{\eta_P\chi}}, \tag{3.21}$$

$$\frac{K}{Z} = \frac{\alpha - 1 + \frac{\alpha}{\eta_P\chi}}{\left(1 - \alpha\varepsilon\right)\left(B - \delta_H - \rho\right) + \left(1 - \alpha\right)\delta_K + \rho}. \tag{3.22}$$

After having calculated the noncooperative and the cooperative outcomes we are able now to determine the cooperation effects on growth, pollution and welfare.

3.3. Cooperation Effects on Growth, Pollution and Welfare

We now can distinguish three different scenarios of cooperation: knowledge cooperation, environmental cooperation and full cooperation. The latter is the globally first-best solution described above. What are the reasons for analyzing partial cooperations? First, it is likely that the negotiation costs differ between the two international spillovers. Second, the public is well informed about one spillover but not about the other because there is less uncertainty about it, or the consequences are more visible. In the extreme, the countries do not know about the second spillover.[7] Finally, partial cooperations are advantageous from a technical point of view since it is easier to show isolated cooperation effects of one spillover.

To assess the effects of the three different cooperative solutions on growth, pollution and welfare we compare the reduced forms of the noncooperative solution (3.6) and (3.9)–(3.12) with the corresponding reduced forms of the cooperative solution (3.16) and (3.19)–(3.22). We see that the noncooperative solution is identical to the full cooperative solution if international spillovers are absent ($\beta = 1$ and $\eta_F = 1$).

There are two possibilities for computing the effects of the different cooperative outcomes. (i) The effects of knowledge cooperation on core variables are similar to the effects of a higher β in the reduced forms of the noncooperative outcome. The effects of environmental cooperation on core variables are similar to the effects of a higher η_F in the reduced forms of the noncooperative solution. Finally, the effects of full cooperation on core variables are similar to the effects of a simultaneous increase of β and η_F in the reduced forms of the noncooperative outcome. Unfortunately, the partial derivatives of the reduced forms with respect to a simultaneous increase of β and η_F are impossible to obtain. (ii) The other possibility to figure out the effects on core variables for a full cooperation is to compare the reduced forms of the noncooperative solution with the reduced forms of the cooperative solution. For the partial cooperations this is done as follows. We can mimic the cooperative outcome for the separate knowledge and pollution agreements by setting $\beta = 1$ and $\eta_F = 1$ in the reduced forms of the noncooperative solution, respectively. For example, to derive the effects of knowledge cooperation we compare every reduced form of the noncooperative solution for $0 < \beta < 1$ with itself, but setting $\beta = 1$. By doing so we obtain the effects of knowledge cooperation on pollution, growth and the consumption-capital ratio. Similarly this can be done for the environmental cooperation

[7] International spillovers could affect the countries asymmetrically, which complicates the negotiation and the success of a full cooperation. However, since we assume identical countries, this is not possible in our framework.

as well. The effects on growth, pollution and the consumption-capital ratio of knowledge, environmental and full cooperation are summarized in Table 3.1 in rows 2-4. The superscript 'nc' indicates the noncooperative solution whereas 'c' indicates the cooperative outcome. In order to analyze welfare changes we integrate the discounted life-time utility function for $\varepsilon \neq 1$ and $\varepsilon = 1$, respectively:

$$U_0 = \frac{1}{1-\frac{1}{\varepsilon}} \left[\frac{P^{-\eta_P\left(1-\frac{1}{\varepsilon}\right)} \left(\frac{C}{K}\right)^{1-\frac{1}{\varepsilon}} K_0^{1-\frac{1}{\varepsilon}}}{\rho - g\left(1-1/\varepsilon\right)} - \rho \right] \quad \text{for} \quad \begin{matrix} \varepsilon > 0 \\ \varepsilon \neq 1 \end{matrix},$$

$$U_0 = \frac{1}{\rho}\ln\frac{C}{K} + \frac{1}{\rho}K_0 - \frac{1}{\rho}\eta_P \ln P + \frac{1}{\rho^2}g \quad \text{for} \quad \varepsilon = 1, \tag{3.23}$$

where the term $[\rho - g\left(1-1/\varepsilon\right)]$ must be positive to rule out explosive consumption paths.[8] From the present-value utility function (3.23) we see that the discounted lifetime utility is a rising function of the consumption-capital ratio and the rate of growth but a decreasing function of pollution. K_0 represents the exogenous initial capital stock at period 0. Inserting the results of Table 3.1 (rows 2–4) in function (3.23) we are now able to analyze the different agreements from a welfare point of view. The effects on welfare are summarized in row 5 of Table 3.1. Before we describe the cooperations effects, recall that in the noncooperative solution all existing *national* externalities are internalized as we have assumed a national benevolent dictator.

	knowledge cooperation	pollution cooperation	full cooperation
growth	$g^{nc} < g^c$	$g^{nc} = g^c$	$g^{nc} < g^c$
pollution	$P^{nc} > P^c$	$P^{nc} > P^c$	$P^{nc} > P^c$
ratio C/K	$\left(\frac{C}{K}\right)^{nc} < \left(\frac{C}{K}\right)^c$	$\left(\frac{C}{K}\right)^{nc} < \left(\frac{C}{K}\right)^c$	$\left(\frac{C}{K}\right)^{nc} < \left(\frac{C}{K}\right)^c$
welfare	$U_0^{nc} < U_0^c$	$U_0^{nc} < U_0^c$	$U_0^{nc} < U_0^c$

Table 3.1: Cooperation effects on core variables, when $P = f(K,Z)$

Knowledge cooperation: The national governments internalize only the external international effect of human capital accumulation to the other country. Therefore, the marginal product of studying increases, this boosts growth in the cooperative solution since the education sector is the engine of growth.[9] Due to the fact that the marginal productivity of human capital increases, final good production becomes more human capital

[8] This is shown, for example, by Barro and Sala-i-Martin (1995, p. 156). The requirement corresponds to the bounded utility condition and rules out explosive consumption paths.

[9] According to the constant returns to scale in the final good sector (2.1), both capital stocks have to

intensive. This leads to a reduced pollution and an increased consumption-capital ratio. Higher growth, a better environmental quality and an increased consumption-capital share increase unambiguously welfare in the knowledge cooperation (see eq. (3.23)).

Environmental Cooperation: The governments internalize only the negative international external effect of pollution. The long-term growth rate is unchanged, pollution decreases, and the consumption-capital ratio increases. The effects on welfare in the case of environmental cooperation are unambiguously positive.

Full cooperation: Since the effects of the partial cooperations on core variables are the same, it is not surprising that the full cooperation (which is a combination of the partial cooperations) has the same effects. Growth rises, environmental quality increases and the consumption-capital ratio increases, which leads to a higher welfare.

4. Final Output as the Polluting Factor

In this section, pollution is assumed alternatively to be a function of total output Y and abatement activities Z. So instead of assuming physical capital to be the dirty factor responsible for generating a negative environmental externality, we now assume output to be responsible for pollution (see eq. (2.8)).

4.1. The Noncooperative Solution

We will skip the maximization problem and the derivation of the first-order conditions since it is analogous to that of Section 3. Along a balanced growth path, the Keynes–Ramsey rule with this pollution specification is given by

$$g = \varepsilon \left[\alpha \left(\frac{Y}{K} - \frac{Z}{K} \right) - \delta_K - \rho \right], \tag{4.1}$$

where all other first-order conditions along a balanced growth path are identical to eqs. (3.4) and (3.6)–(3.8). The same applies for the reduced forms of the growth rate and the fraction of time devoted to production. They are identical to eqs. (3.6) and (3.9). However, the reduced forms of the consumption-capital ratio, of the output-capital ratio and of the output-abatement ratio are now given by

$$\frac{C}{K} = \frac{(1-\alpha\varepsilon)(\beta B - \delta_H - \rho) + (1-\alpha)\delta_K + \rho}{\alpha}, \tag{4.2}$$

grow with the same rate along a balanced growth path. However, the growth rate of human capital stock is determined solely in the education sector (2.3). Therefore, human capital is the engine of growth in the Uzawa–Lucas model.

$$\frac{Y}{K} = \frac{\Psi_1 (\beta B - \delta_H + \delta_K) + \chi \eta_P \alpha [(\varepsilon - 1)\delta_K + \varepsilon \rho]}{\alpha (2 - \eta_F)}, \tag{4.3}$$

$$\Psi_1 \equiv [(2 - \eta_F) + \chi \eta_P (1 - \alpha \varepsilon)]$$

$$\frac{Y}{Z} = 1 + \frac{(2 - \eta_F)(\beta B - \delta_H + \delta_K)}{\chi \eta_P [(1 - \alpha \varepsilon)(\beta B - \delta_H - \rho) + (1 - \alpha)\delta_K + \rho]}. \tag{4.4}$$

4.2. The Cooperative Solution

The Keynes–Ramsey rule of the cooperative solution along a balanced growth path is identical to the one of the noncooperative solution (4.1); note, however, that the output-capital ratio and the abatement-capital ratio are determined differently as we shall see in the following. The other first-order conditions are identical to eqs. (3.14) and (3.16)–(3.18). The reduced forms of the growth rate and of the fraction of time devoted to production are identical to (3.16) and (3.19), respectively. The remaining reduced forms of C/K, Y/K and Y/Z are given by

$$\frac{C}{K} = \frac{(1 - \alpha \varepsilon)(B - \delta_H - \rho) + (1 - \alpha)\delta_K + \rho}{\alpha}, \tag{4.5}$$

$$\frac{Y}{K} = \frac{\Psi_2 (B - \delta_H + \delta_K) + \chi \eta_P \alpha [\varepsilon \rho + (\varepsilon - 1)\delta_K]}{\alpha}, \tag{4.6}$$

$$\Psi_2 \equiv [1 + \chi \eta_P (1 - \alpha \varepsilon)]$$

$$\frac{Y}{Z} = 1 + \frac{B - \delta_H + \delta_K}{\eta_P \chi [(1 - \alpha \varepsilon)(B - \delta_H - \rho) + (1 - \alpha)\delta_K + \rho]}. \tag{4.7}$$

4.3. Cooperation Effects on Growth, Pollution and Welfare

In the following we distinguish between the effects of knowledge cooperation, environmental cooperation and full cooperation. Comparing the reduced forms again we see that the noncooperative solution is identical to the full cooperative solution for $\beta = 1$ and $\eta_F = 1$. The cooperative outcome for the knowledge and environmental cooperations can be mimicked by setting $\beta = 1$ and $\eta_F = 1$ in the reduced forms of the noncooperative solution, respectively. The discounted present value of utility is identical to eq. (3.23). The effects on growth, pollution, the consumption-capital ratio and welfare are summarized in Table 4.1.

Due to *knowledge cooperation* the marginal product of studying increases which boosts growth in the cooperative solution since the education sector is the engine of growth. The increased marginal productivity of human capital in the education sector leads to a more

	knowledge cooperation	environmental cooperation	full cooperation
growth	$g^{nc} < g^c$	$g^{nc} = g^c$	$g^{nc} < g^c$
pollution	$P^{nc} < P^c$	$P^{nc} > P^c$	ambiguous
ratio C/K	$\left(\frac{C}{K}\right)^{nc} < \left(\frac{C}{K}\right)^c$	$\left(\frac{C}{K}\right)^{nc} = \left(\frac{C}{K}\right)^c$	$\left(\frac{C}{K}\right)^{nc} < \left(\frac{C}{K}\right)^c$
welfare	ambiguous	$U^{nc} < U^c$	$U^{nc} < U^c$

Table 4.1: Cooperation effects on core variables, when $P = f(Y,Z)$

human capital-intensive final good production and to an increased consumption-capital ratio. Since final good production increases – responsible for the environmental externality – pollution rises. The welfare effects are ambiguous due to the trade-off between growth and pollution. Higher growth and an increased consumption-capital ratio increase welfare, whereas higher pollution decreases welfare ceteris paribus (see eq. (3.23)).

An *environmental cooperation* does not affect the engine of growth. Therefore, the long-term growth rate is unchanged. Pollution decreases but the consumption-capital ratio is unchanged. The effects on welfare in the case of environmental cooperation are unambiguously positive.

Under *full cooperation*, growth rises and the capital-consumption ratio increases; however, the effect on pollution is ambiguous. Depending on the relative strength of the two international spillovers, pollution may rise in the case of full cooperation. Nevertheless, welfare increases since full cooperation is equivalent to a first-best solution.

Spillovers exist because of missing markets. Knowledge spillovers, for instance in the form of new inventions, can be internalized by the creation of patent markets. Obviously international knowledge spillovers require a supranational patent authority vested with the required competencies to guard and to enforce international patent treaties. To a large extent such organizations exist. For instance the 'European Patent Office' (EPO), established in 1977, protects patents within 18 European countries. Furthermore, European patents are also granted on the basis of international applications filed under the 'Patent Cooperation Treaty'. The Patent Cooperation Treaty is one of the various multilateral treaties dealing with the legal and administrative aspects of intellectual property rights which are administrated by the intergovernmental 'World Intellectual Property Organization' (WIPO). State membership of WIPO was more than 170 in August 1998.[10] In addition, the EPO possesses a trilateral cooperation with the 'Japanese Patent Office'

[10] Data is taken from the official web site of the World Intellectual Property Organization (http://www.wipo.org/eng/main.htm).

and the 'United States Patent and Trademark Office' which cover 80 per cent of the world patents.[11] Given these facts it seems plausible to state that many international knowledge spillovers are already internalized. However, apart from the Montreal Protocol on the protection of the ozone layer (1986) no substantial international environmental cooperation has been implemented so far. Thus one can argue that knowledge cooperation best describes the real world in our model. From our analysis with the output-induces pollution specification it is seen that knowledge cooperation unambiguously boosts growth but causes deterioration in the environmental quality. Thus our model suggests that among other things the creation of international patent markets is responsible for environmental degradation. Furthermore, the effects on welfare of knowledge cooperation are ambiguous and depend on parameter values. This is a typical second-best result: the correction of one distortion in the presence of other distortions does not necessarily improve welfare (see Lipsey and Lancaster 1956). Hence the internalization of the knowledge spillover by means of an international patent market may decrease welfare. Finally we can state that the presence of international patent markets may even increase the need for environmental cooperation which would then unambiguously increase welfare.

5. Summary

In this paper we considered international knowledge spillovers and international environmental externalities, and analyzed the strategic interactions between two identical countries within the framework of a differential game. By doing so we have taken into account the fact that many of the most pressing environmental externalities are international rather than national in nature and no supranational authority exists vested with the required competencies to internalize these externalities. Furthermore, we have taken into consideration the effects of international knowledge spillovers on total factor productivity, as empirical evidence suggests. Every country was mutually affected from positive international knowledge spillovers and negative international environmental externalities. Starting from the noncooperative open-loop Cournot–Nash equilibrium we investigated the effects of environmental cooperation, knowledge cooperation and full cooperation.

We have seen that some results concerning pollution and welfare of certain cooperations depend on the chosen pollution specification. However, the results summarized in Table 5.1 are independent of the assumed pollution causing factor: We showed that environmental cooperation improves welfare unambiguously since pollution reduction is

[11] Data and information is taken from the official web site of the European Patent Office (http://www.european-patent-office.org).

	knowledge cooperation	environmental cooperation	full cooperation
growth	$g^{nc} < g^c$	$g^{nc} = g^c$	$g^{nc} < g^c$
pollution		$P^{nc} > P^c$	
welfare		$U^{nc} < U^c$	$U^{nc} < U^c$

Table 5.1: Cooperation effects on core variables, independent of pollution specification

possible without harming growth. However, the effects of knowledge cooperation depend on the chosen pollution function, that is, whether pollution is a side product of physical capital or of final good production. If output is responsible for pollution we found that knowledge cooperation increases growth at the expense of environmental quality; hence the effects on welfare are ambiguous. Thus, our model suggests that among other things the existence of international patent markets is partly responsible for the environmental degradation nowadays. Therefore it is uncertain whether the creation of a patent market in the past increased welfare. However, if pollution is assumed to be a function of physical capital, the pessimistic result changes to a positive one. By assuming this pollution specification, knowledge cooperation boosts not only growth but also reduces pollution and increases welfare. If this pollution specification describes best the real world in our model, the creation of a patent market increased growth and at the same time increased environmental quality. Obviously, both effects raise welfare. Hence, whether the creation of international patent markets tends to improve or tends to reduce environmental quality depends on the pollution specification. Why are the results concerning the environment less optimistic in the case where pollution is a function of output? Given a certain level of output and abatement, with this specification there is no possibility of reducing pollution by choosing a different input ratio in final good production. On the other hand if pollution is generated by physical capital, pollution can be reduced by a more labor-intensive production without lowering output or increasing abatement activities. This missing substitution possibility in the former case is responsible for the different effects of cooperation on the environmental quality. Finally, we compare the effects of full cooperation for both pollution specifications. Our model suggests that full cooperation increases growth unambiguously independent of the pollution specification. However, whereas environmental quality increases if pollution is generated by physical capital, the effect becomes ambiguous and depends on the relative strength of both spillovers if pollution is generated by output.

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