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Trade, Growth, and Environmental Quality*

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Abstract

This paper examines linkages between international trade, environmental degradation, and economic growth in a dynamic North–South trade game. Using a neoclassical production function subject to an endogenously improving technology, North produces manufactured goods by employing labor, capital, and a natural resource that it imports from South. South extracts the resource using raw labor, in the process generating local pollution. We study optimal regional policies in the presence of local pollution and technology spillovers from North to South under both non-cooperative and cooperative modes of trade. Non-cooperative trade is inefficient due to stock externalities. Cooperative trade policies are efficient and yet do not benefit North. Both regions gain from improved productivity in North and faster knowledge diffusion to South regardless of the trading regime.

1. Introduction

Natural resources are an important component of world trade. To many less developed countries they are a critical source of foreign exchange, while to many developed economies they are indispensable factors of production. As a consequence, natural resource policy inevitably involves strategic aspects that can be conveniently analyzed as a dynamic game between the industrial North and the less developed South. The key elements of this game are that the natural resource is supplied by the South using labor of which it has a surplus endowment. North requires the natural resource as an essential input for its industrial output, part of which it trades to the South for their consumption.

One important aspect of the trading relationship that we envision is that the decisions of both regions involve potential externalities that they are likely to impose. First, the extraction of the resource is likely to cause significant persistent or even irreversible environment damage. In this regard, in making its production decisions and thereby generating its demand for the natural resource, the North is likely to cause pollution in the South, a fact that it ignores in making its decision-making. For its part, the South, being the sole supplier of the natural resource, has monopoly power, that it finds optimal to exploit in setting the price at which it is willing to trade. By ignoring these spillover effects, the time paths generated by non-cooperative behavior are likely to be dynamically inefficient.

The relationship between trade policy, economic growth, and the environment has evolved into a long literature, exploring many issues. Using a differential game framework, Galor (1986) focuses on the slower growth rate that results when North and

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South trade non-cooperatively. Chichilnisky (1994) emphasizes ill-defined property rights over South's resources which gives rise to over-exploitation of South's environment. A resource monopoly is desirable as it would curb pollution, but it is also inefficient as it will hamper economic growth. Grossman and Helpman (1991) draw attention to the beneficial effects of trade on research and development and capital accumulation. Alemdar and Ozyildirim (1998, 2002) note that the unwanted effect of a resource monopoly is mitigated when trade is accompanied by knowledge spillovers to the South.[1]

Also, many studies inquire about the feasibility of sustained economic growth when environment acts as a natural constraint (e.g. Gradus and Smulders, 1993; Bovenberg and Smulders, 1995). These studies, however, either ignore trade relationships between regions or assume that they are identical (e.g. Hettich, 2000).

In this paper we focus on the strategic aspects of trade in natural resources by extending the standard dynamic North–South model to one in which production in the North takes place in two sectors: a final output sector and a knowledge-producing sector. Both sectors are general with respect to their respective returns to scale, and indeed, the productive side of the North economy is characteristic of the recent non-scale growth models, pioneered by Jones (1995) and further developed by Eicher and Turnovsky (1999). An important feature of our analysis is that as knowledge accumulates in the North it facilitates the abatement of pollution in the South, and to capture this critical role satisfactorily is the reason for the disaggregation of North's production.

Our analysis proceeds in two stages. First, we set out the analytical solution and characterize the equilibrium dynamics.[2] Then, the dynamic responses to various structural changes are analyzed and compared with the efficient paths. Specifically, we consider (i) a 30% productivity increase in the knowledge-producing sector, (ii) a tripling in the applicability of knowledge to pollution reduction in the South, and (iii) a doubling in the environmental damage rate of the natural resource.

Owing to the inefficiencies that accompany the non-cooperative mode of trade, global welfare is substantially lower under non-cooperation than it is under cooperation. Also noteworthy is the fact that a regime switch from a cooperative to a non-cooperative trade regime, while always reducing South's welfare, increases North's welfare. Consequently, not only is North unwilling to cooperate, but also the inefficiencies that arise from such a reluctance are severe. South sets the resource price to internalize the local cost of pollution as well as to extract monopoly rent from North. From a global perspective, to the extent that North also cares about South's environment, resource prices would be inefficiently low because they would reflect only the local cost of pollution. But then, this would be partly alleviated thanks to the exercise of monopoly power by the South. Thus, insofar as North cares about South's environment, South's monopoly is not that bad after all.

North, on the other hand, decides on a resource allocation so as to maximize its own welfare. Resources allocated to the production of final goods yield immediate higher consumption while resources that are employed in the technology sector will yield higher consumption only in the future. Given that delaying consumption is costly, that resources that pollute South are employed only in the final goods production, and that neither region internalizes the knowledge spillover, all lead to an inefficiently small knowledge sector from a global perspective. As a result, an excess production of final goods cause an over-accumulation of physical capital and an over-use of resources, the latter ultimately leading to an excessive level of pollution in the South.

Indeed, the same results are replicated under various parameter configurations, attesting to the fact that knowledge spillovers can be a significant source of distortions in global growth. Further, although the pollution we consider is local in nature, nonetheless it has global ramifications for growth when coupled with knowledge spillovers. All else being the same, an increased rate of knowledge diffusion in the South makes resource extraction less costly, leading to lower prices and thus faster accumulation of both physical capital and knowledge in the North. Conversely, North's growth can be checked if resource extraction creates more damage to South's environment. Trade between the regions acts as a conduit for the local changes to be transmitted to the other side.

2. The Model

Non-Cooperative North/South Trade

The global economy comprises two regions, North and South. Each region is populated with infinitely-lived identical individuals, L_N in North and L_S in South, which grow at the exogenous rates, $\dot{L}_N/L_N = n_N$ and $\dot{L}_S/L_S = n_S$, respectively. Since our main interest lies in the analysis of how various sources of inefficiencies interact to distort growth trajectories in an aggregative dynamic game framework, we adopt the social planning paradigm.

The North produces a final good, Y, that can be either consumed, invested, or exported to the South at a fixed price of unity. Manufactured goods are produced using labor, capital, technology (knowledge), A, and a raw material (resource), R, using a Cobb–Douglas production function:

$$Y = \phi_Y A^{\alpha_A}[uL_N]^{\alpha_L}[vK]^{\alpha_K} R^{\alpha_R}, \tag{1}$$

where ϕ_Y is an exogenous technological shift parameter, $\alpha_i, 0 < \alpha_i < 1$ $(i = A, L, K, R)$ are the productive elasticities, while u and v are the respective fractions of labor and capital employed in the final good sector. Raw material is imported from the South.

New knowledge is produced in the technology sector by employing labor and capital, together with the existing technology, while existing knowledge depreciates at a constant rate, δ_A. Thus the state of technology evolves according to:

$$\dot{A} = \phi_A A^{\beta_A}[(1-u)L_N]^{\beta_L}[(1-v)K]^{\beta_K} - \delta_A A \equiv J - \delta_A A, \tag{2a}$$

where ϕ_A reflects the technology level and β_i, $0 < \beta_i < 1$ $(i = A, L, K)$ are productive elasticities.

Equilibrium in North's final good sector is described by:

$$\dot{K} = Y - C_N - C_S - \delta_K K. \tag{2b}$$

This equation asserts that North's final output is either consumed in the North, C_N, exported to the South, C_S, allocated to replace depreciated capital, $\delta_K K$, or accumulated as new capital, $\dot{K}$. South finances its purchase of consumption imports by the export of raw materials, which it sells at the relative price p (South's terms of trade), over which it has a monopoly. We assume that trade between the two regions is balanced, so that

$$C_S = pR, \tag{3}$$

implying

$$\dot{K} = Y - C_N - pR - \delta_K K. \tag{2b'}$$

Equation (2b′) indicates that by controlling its terms of trade, South can indirectly influence the pace of physical capital accumulation in the North.

North's planner takes the South's terms of trade as given and is assumed to maximize the intertemporal utility of the representative agent, namely,

$$\max_{C_N,u,v,R} J_N = \int_0^\infty (1/\gamma_N)(C_N/L_N)^{\gamma_N} e^{-\rho_N t} dt, \quad \gamma_N < 0, \rho_N > 0, \tag{4}$$

subject to the production and the accumulation constraints (1), (2a), (2b′), $K(0) = K_0$, $A(0) = A_0$, and $C_N \geq 0$. C_N/L_N is per capita consumption, and ρ_N denotes the North's rate of time preference. The parameter γ_N is related to North's intertemporal elasticity of substitution, s_N say, by $s_N = (1 - \gamma_N)^{-1}$, so that the restriction $\gamma_N < 0$ implies $s_N < 1$, an assumption broadly consistent with the empirical evidence.

The South is a small developing economy that has no capital. Its sole economic activity lies in producing the raw material, which is done by employing labor alone in accordance with the constant-returns-to-scale production function:[3]

$$R(t) = bL_S(t). \tag{5}$$

South's production is unconstrained by labor availability, $L_S(t)$.[4] Thus, what we have in mind is a typical small oil-producing economy that finances its consumption out of its oil revenues.[5]

Resource extraction causes pollution which accumulates locally and is internalized only in the South. However, technology accumulated in the North diffuses to the South to reduce this damage, albeit at a diminishing rate. Thus, the resulting patterns of trade and growth are further complicated due to the presence of local externalities.

The level of pollution in the South, P, evolves in accordance with:

$$\dot{P} = (1/\theta) R^\theta A^{-\varepsilon} - \delta_P P, \tag{6}$$

where $\theta > 1$ measures the order of environmental damage due to extraction, $0 < \varepsilon < 1$ is a technology diffusion (spillover) parameter signifying the degree of applicability of technology to pollution reduction, and $0 < \delta_P < 1$ denotes the constant instantaneous rate at which pollution decays naturally.[6]

In addition to per capita consumption, the utility of South's representative agent depends inversely upon the stock of pollution, P. Facing North's demand for the resource, South's planner takes North's policies as given and chooses terms of trade to maximize South's welfare, namely:

$$\max_p J_S = \int_0^\infty \left[(1/\gamma_S)(C_S/L_S)^{\gamma_S} - DPL_S^{-\tau}\right] e^{-\rho_S t} dt, \quad \gamma_S < 0, \rho_S > 0, D > 0, \tag{7}$$

subject to (1), (2b), (3), and (6), $P(0) = P_0$, $K(0) = K_0$, and $C_s \geq 0$, where ρ_S is South's rate of time preference. The exponent $0 < \tau < 1$ reflects the degree to which South's representative agent perceives pollution as a public bad, and D converts pollution into units of utility. Following Eriksson and Zehaie (2005), we shall call the ratio P/L_S^τ the perceived pollution. Note that $\tau = 0$ corresponds to the case where pollution exhibits pure *public* bad characteristics: if both pollution and population are doubled, the pollution that each individual suffers from doubles as well. On the other hand, $\tau = 1$ corresponds to the case where pollution exhibits pure *private* bad characteristics; doubling pollution and the population results in no more disutility of pollution per person.

Cooperative North/South Trade

In designing cooperative strategies, North and South must agree in advance as to how they will share the potential gains from cooperation. The distributive outcome will depend on the weights, ω, that are attached to the respective welfares. The determination of the value of ω most likely to prevail in a cooperative agreement requires a bargaining framework which recognizes the relative power of the participants. This is outside the scope of our inquiry. Instead, to enable welfare comparisons across scenarios, we assume exogenously given weights. The Pareto-efficient solution is found by choosing C_N, u, v, R, and p to maximize:

$$J=\omega\int_0^{\infty}(1/\gamma_N)(C_N/L_N)^{\gamma_N}e^{-\rho_N t}dt+(1-\omega)\int_0^{\infty}\left[(1/\gamma_S)(C_S/L_S)^{\gamma_S}-DPL_S^{-\tau}\right]e^{-\rho_S t}dt, \tag{8}$$

subject to (1), (2a), (2b), (3), and (6), $A(0)=A_0$, $P(0)=P_0$, $K(0)=K_0$, and $C_N, C_S \geq 0$.

Cooperation between North and South needs to be supported by binding agreements. Precommitment is difficult in the absence of suitable institutions that can enforce global decisions. Nonetheless, cooperative solutions, though lacking credibility, are important insofar as they indicate the welfare losses that are likely to ensue given a lack of commitment.

3. The Analytical Solution

Given the returns-to-scale properties of the underlying production functions, the long-run equilibrium of the trade game, be it cooperative or non-cooperative, is not stationary, but will involve steady growth that reflects the underlying technology and preference structure. Consequently, in order to express the model in terms of stationary quantities it needs to be appropriately scaled to reflect the equilibrium of ongoing growth; see Eicher and Turnovsky (1999). To that end, and irrespective of the trading regime, we envisage a steady-state equilibrium in which a number of balanced growth conditions hold. First, since the final goods, Y, are either consumed in the North, C_N, or in the South, C_S, or invested as physical capital, K, they will all grow at the same rate. Second, for a balanced growth to exist, it is required that the benefits from per capita consumption relative to the disutility from pollution at the margin have to remain constant in the South. Consequently, technology, A, the pollution stock, P, raw materials, R, and the relative price, p, will all grow at different constant rates.

Given these assumptions, we first time-differentiate the production function and the instantaneous utility of South. Making the necessary substitutions from equations (2a), (2b), and (6), we obtain the following balanced growth rates (denoted by "^"):

$$\hat{Y}=\hat{K}=\hat{C}_N=\hat{C}_S=\left\{\frac{[\alpha_A+(\varepsilon/\theta)\alpha_R]\beta_L+[\alpha_L+(\alpha_R n_S(\tau-\gamma_S)/\theta n_N)](1-\beta_A)}{[1-\alpha_K-\alpha_R(\gamma_S/\theta)](1-\beta_A)-[\alpha_A+\alpha_R(\varepsilon/\theta)]\beta_K}\right\}n_N \equiv g_Y n_N, \tag{9a}$$

$$\hat{A}=(1-\beta_A)^{-1}(\beta_L+\beta_K g_Y)n_N \equiv g_A n_N, \tag{9b}$$

$$\hat{P}=[\gamma_S g_Y+(\tau-\gamma_S)(n_S/n_N)]n_N \equiv g_P n_N, \tag{9c}$$

$$\hat{R}=\theta^{-1}(\varepsilon g_A+g_P)n_N \equiv g_R n_N, \tag{9d}$$

$$\hat{p} = \hat{C}_S - \hat{R} \equiv \theta^{-1}(1-\beta_A)^{-1}[(\theta(1-\beta_A)-\varepsilon\beta_K)g_Y - \varepsilon\beta_L]n_N \equiv g_p n_N, \tag{9e}$$

and g_i, $i = Y, A, P, R, p$ are the respective growth factors.

These long-run equilibrium growth rates have been written in a recursive form. First, (9a) expresses the common long-run growth rate pertaining to production, capital accumulation in the North, and consumption in the two regions. Given g_Y, (9b) to (9e) then yield the corresponding expressions for the growth rate of technology, pollution, resource extraction, and the relative price. As a general observation, all the structural parameters have broad effects on the growth rates, reflecting the high degree of interaction between the two economies. Thus, even though North is indifferent to South's pollution when choosing its optimal policies, nonetheless, some pollution parameters enter as determinants of North's long-run consumption, capital, output and technology growth rates. Notably, in an environment in which steady-state growth is possible, a change in the technology spillover or in the environmental damage rate in the South, affects not only the levels of North's optimal policies, but also their permanent growth rates.

In particular, the following features of the equilibrium merit comment. First, $\partial\hat{Y}/\partial\theta < 0$ and $\partial\hat{Y}/\partial\varepsilon > 0$, implying that an increase in the long-run rate of environmental damage due to extraction in the South has an adverse effect on the growth rate of output and consumption, while an improvement in the technology of pollution reduction raises the long-run growth rate. This is because more pollutant resources are compensated by higher prices choking North's growth, whereas environmentally-friendlier technologies are reciprocated by lower resource prices and thereby faster growth. Second, an increase in the growth rate of North's final output tends to raise the growth rates of knowledge and of resource extraction, as well as the growth rate of the relative price.

An interesting aspect concerns the long-run behavior of pollution. To simplify things, we assume the plausible case of a common population growth rate, $n_N = n_S$, in which case $\text{sgn}(\hat{P}) = \text{sgn}[\gamma_S(g_Y - 1) + \tau]$. Thus, whether the long-run equilibrium is associated with positive or negative growth of pollution in the South depends upon (i) the growth rate in the North, and (ii) South's perception of pollution as a "bad."

To discuss the transitional dynamics, we transform each variable so that it is stationary in the steady state. Thus, we define the scaled variables as: $y \equiv Y/L_N^{g_Y}$, $k \equiv K/L_N^{g_Y}$, $c_n \equiv C_N/L_N^{g_Y}$, $a \equiv A/L_N^{g_A}$, $r \equiv R/L_N^{g_R}$, $p^* \equiv p/L_N^{(g_Y - g_R)}$, $P^* \equiv P/L_N^{g_P}$. For convenience, we shall refer to $y, k, c_n, a, r, p^*, c_s \equiv p^*r$, and P^* as *scale-adjusted* quantities.[7] Now, we can rewrite the scale-adjusted output, and the accumulation of technology, physical capital, and pollution stock as:

$$y = \phi_Y a^{\alpha_A} u^{\alpha_L} (vk)^{\alpha_K} r^{\alpha_R}, \tag{10a}$$

$$\dot{a} = \phi_A a^{\beta_A}(1-u)^{\beta_L}[(1-v)k]^{\beta_K} - \delta_A^* a \equiv j - \delta_A^* a, \quad \delta_A^* = \delta_A + n_N g_A, \tag{10b}$$

$$\dot{k} = y - c_n - p^* r - \delta_K^* k, \quad \delta_K^* = \delta_K + n_N g_Y, \tag{10c}$$

$$\dot{P}^* = (1/\theta) r^{\theta} a^{-\varepsilon} - \delta_P^* P^*, \quad \delta_P^* = \delta_P + n_N g_P. \tag{10d}$$

Open-Loop Nash Equilibrium Solution

We begin by considering the open-loop Nash equilibrium solution of the non-cooperative trade game. After transforming the variables in (4) into the scale-adjusted quantities, North's planning problem can be expressed as choosing its rate of consumption, c_n, its demand for resources, r, allocation of labor and capital, u and v, and rates of accumulation of capital, $\dot{k}$, and technology, $\dot{a}$, to maximize:

$$J_N = \int_0^\infty (1/\gamma_N) c_n^{\gamma_N} e^{-\rho_n t} dt, \quad \rho_n = \rho_N - (g_Y - 1)\gamma_N n_N, \tag{11}$$

subject to (10a) to (10c), $c_n \geq 0$, $k(0) = k_0$, and $a(0) = a_0$, where South's terms of trade are taken as given. Performing the optimization, the following necessary conditions obtain:

$$c_n^{\gamma_N - 1} = \lambda_1, \tag{12a}$$

$$\lambda_1 \alpha_L (y/u) = \lambda_2 \beta_L (j/(1-u)), \tag{12b}$$

$$\lambda_1 \alpha_K (y/v) = \lambda_2 \beta_K (j/(1-v)), \tag{12c}$$

$$\alpha_R (y/r) = p^*, \tag{12d}$$

$$\alpha_K (y/k) + (\lambda_2/\lambda_1) \beta_K (j/k) - \delta_K^* = \rho_n - \left(\dot{\lambda}_1/\lambda_1\right), \tag{12e}$$

$$\beta_A (j/a) + (\lambda_1/\lambda_2) \alpha_A (y/a) - \delta_A^* = \rho_n - \left(\dot{\lambda}_2/\lambda_2\right), \tag{12f}$$

$$\lim_{t\to\infty} e^{-\rho_n t} \lambda_1 k = 0, \quad \lim_{t\to\infty} e^{-\rho_n t} \lambda_2 a = 0, \tag{12g}$$

where λ_1, λ_2 are the shadow values of aggregate physical capital and knowledge, respectively.

Equation (12a) states that along the optimal paths the marginal utility of consumption should equal the shadow value of physical capital at every point in time. Equations (12b) and (12c) determine the sectoral allocations of labor and capital so that their respective marginal products are equated across sectors. Equation (12d) asserts that the marginal product of the resource must equal its cost, p. The next two equations describe the two arbitrage conditions. The first equates the net return to physical capital to the return on consumption, both measured in terms of the final output. Analogously, (12f) requires that the return on technology be equated to the return on consumption, both expressed in units of knowledge. Finally, (12g) expresses the transversality conditions.

Combining (12d) with (10a), North's demand for the natural resource can be expressed as

$$r = \left(\alpha_R \phi_Y a^{\alpha_A} u^{\alpha_L} (vk)^{\alpha_K}\right)^{1/(1-\alpha_R)} (p^*)^{-1/(1-\alpha_R)}. \tag{13}$$

From equations (10a), (10b), (12b), and (12c), the optimal shares of labor and capital in the final good production are $u = u(\lambda_1, \lambda_2, a, k)$ and $v = v(\lambda_1, \lambda_2, a, k)$. These can be shown to imply that an increase in the stock of physical capital or technology raises the productivity of both sectors in proportion to an amount that depends upon the respective productive elasticity. Resources therefore move toward the sector in which that input has the greater production elasticity.

Faced with North's demand for the resource, given by (13), and taking North's policies as given, South's planner chooses a path of scale-adjusted terms of trade to maximize South's welfare:

$$\max_{p^*} J_S = \int_0^\infty ((1/\gamma_S) c_s^{\gamma_S} - DP^*) e^{-\rho_s t} dt, \quad \rho_s = \rho_S - (g_Y n_N - n_S)\gamma_S, \tag{14}$$

subject to (10a), (10c), and (10d), $c_s \geq 0$, $k(0) = k_0$, and $P^*(0) = P_0^*$.

The necessary optimality conditions for the South are:

$$c_s^{\gamma_S - 1} = -(1-\alpha_R)\alpha_R^{-1}\mu_1 - \left(\alpha_R p^* a^\varepsilon\right)^{-1} r^{\theta-1}\mu_2, \tag{15a}$$

$$\alpha_K \frac{y}{k} - \delta_K^* + \frac{\mu_2}{\mu_1}\frac{r^\theta}{a^\varepsilon}\frac{\alpha_K}{(1-\alpha_R)k} + \frac{1}{\mu_1}\frac{\alpha_K}{(1-\alpha_R)k} c_s^{\gamma_S} = \rho_s - \frac{\dot{\mu}_1}{\mu_1}, \tag{15b}$$

$$-(D\mu_2^{-1} + \delta_P^*) = \rho_s - (\dot{\mu}_2/\mu_2), \tag{15c}$$

$$\lim_{t\to\infty} e^{-\rho_s t}\mu_1 k = 0, \quad \lim_{t\to\infty} e^{-\rho_s t}\mu_2 P^* = 0, \tag{15d}$$

where μ_1, μ_2 are the respective shadow values of the stocks of physical capital and pollution.

From equation (15a), South's optimal terms of trade must be so chosen so that the sum of incremental benefits from consumption and physical capital equals the marginal cost of pollution. Note from equation (15b), that the value of an extra unit of physical capital stock in the South, not surprisingly, evolves differently from the North insofar as the former internalizes the interaction between capital and pollution accumulation. Equation (15c), on the other hand, shows how the marginal social cost of pollution will evolve as pollution itself accumulates over time. Remembering that along the balanced growth path scale-adjusted pollution is constant, and solving for μ_2 from equation (15c), the transversality condition (15d) is satisfied only if the equilibrium shadow value of the scaled pollution is equal to $-D/(\delta_P^* + \rho_s)$ throughout.

Next, we consider the Nash equilibrium of this game at the steady state. A joint stationary solution of the optimality conditions for both regions determines the long-run equilibrium of the trade game. Hence, assuming steady state, the following set of equations constitutes the Nash equilibrium where the stationary variables are denoted by "~":

$$\left(\tilde{y}/\tilde{k}\right) - \left(\tilde{c}_n/\tilde{k}\right) - \left(\tilde{p}^*\tilde{r}/\tilde{k}\right) - \delta_K^* = 0, \tag{16a}$$

$$\left(\tilde{j}/\tilde{a}\right) - \delta_A^* = 0, \tag{16b}$$

$$(1/\theta)\left(\tilde{P}^*\tilde{a}^\varepsilon\right)^{-1}\tilde{r}^\theta - \delta_P^* = 0, \tag{16c}$$

$$\alpha_R(\tilde{y}/\tilde{r}) - \tilde{p}^* = 0, \tag{16d}$$

$$\tilde{v}-(\alpha_K\beta_L\tilde{u})[\alpha_K\beta_L\tilde{u}+\alpha_L\beta_K(1-\tilde{u})]^{-1}=0, \tag{16e}$$

$$\alpha_K(\tilde{y}/\tilde{k})-\delta_K^*+\beta_K\alpha_L(1-\tilde{u})(\beta_L\tilde{u})^{-1}(\tilde{y}/\tilde{k})-\rho_n=0, \tag{16f}$$

$$\beta_A(\tilde{j}/\tilde{a})-\delta_A^*+(\alpha_A\beta_L\tilde{u})[(1-\tilde{u})\alpha_L]^{-1}(\tilde{j}/\tilde{a})-\rho_n=0, \tag{16g}$$

$$-\alpha_R(\tilde{p}^*\tilde{r})^{\gamma_S}-\frac{\alpha_K\tilde{p}^*\tilde{r}((\tilde{p}^*\tilde{r})^{\gamma_S}-[\tilde{a}^{\varepsilon}(\rho_s+\delta_P^*)]^{-1}\tilde{r}^{\theta}D)}{\tilde{k}(\rho_s+\delta_K^*-\alpha_K(\tilde{y}/\tilde{k}))}+\frac{\tilde{r}^{\theta}D}{\tilde{a}^{\varepsilon}(\rho_s+\delta_P^*)}=0. \tag{16h}$$

We proceed to solve the system of equations as follows. First, we obtain the equilibrium growth rate of technology, $\tilde{j}/\tilde{a}=\tilde{J}/\tilde{A}$ from (16b). Given the growth rate of technology, (16g) then implies the stationary sectoral allocation of labor, $\tilde{u}$. Having derived $\tilde{u}$, we use (16e) and (16f) to solve for the long-run sectoral allocation of capital, $\tilde{v}$, and the output–capital ratio, $\tilde{y}/\tilde{k}$, respectively. Given $\tilde{y}/\tilde{k}$, the ratio of the South's consumption to capital, $\tilde{p}^*\tilde{r}/\tilde{k}$ can now be derived from (16d). Knowing $\tilde{y}/\tilde{k}$ and $\tilde{p}^*\tilde{r}/\tilde{k}$, (16a) determines the ratio of the North's consumption to capital, $\tilde{c}_n/\tilde{k}$, while (16c) and (16h) determine the ratio $\tilde{P}^*/\tilde{k}^{\gamma_S}$. Given $\tilde{P}^*/\tilde{k}^{\gamma_S}$, $\tilde{u}$, and $\tilde{v}$, the ratio $\tilde{r}^{\theta}/\tilde{k}^{\gamma_S+\varepsilon\beta_K/(1-\beta_A)}$ can be obtained from (16b) and (16c). We use the production function for the final good and (16b) to find the stock of capital, $\tilde{k}$, given $\tilde{r}^{\theta}/\tilde{k}^{\gamma_S+\varepsilon\beta_K/(1-\beta_A)}$, $\tilde{y}/\tilde{k}$, $\tilde{u}$, and $\tilde{v}$. Having obtained $\tilde{k}$, $\tilde{a}$ and $\tilde{r}$ are derived from (16b) given $\tilde{u}$ and $\tilde{v}$ and the ratio $\tilde{r}^{\theta}/\tilde{k}^{\gamma_S+\varepsilon\beta_K/(1-\beta_A)}$. Finally, given $\tilde{r}$ and $\tilde{p}^*\tilde{r}/\tilde{k}$ we solve for $\tilde{p}^*$.

Open-Loop Cooperative Solution

In order for the cooperative equilibrium to exist, it is necessary that the scale-adjusted discount rates be the same for both regions; $\rho_n=\rho_s=\rho$. Although this condition is not required for non-cooperative equilibrium, nonetheless we choose parameter values to satisfy this requirement so that we can compare the equilibria under cooperative and non-cooperative modes of trade.

The Pareto-efficient paths maximize the weighted sum of welfares:

$$\max_{c_n,p^*,r,u,v} J=\int_0^{\infty}[\omega(1/\gamma_N)c_n^{\gamma_N}+(1-\omega)((1/\gamma_S)c_s^{\gamma_S}-DP^*)]e^{-\rho t}dt, \tag{17}$$

subject to (10a) to (10d), $c_n, c_s\geq 0$, $k(0)=k_0$, $a(0)=a_0$, and $P^*(0)=P_0^*$. Although, at first blush this may seem like a straightforward optimization problem, in contrast with the non-cooperative mode of the game, any attempt at solution defies this early optimism. Unfortunately, the steady state of the model does not admit a closed-form solution unless $\omega=0.5$ and $\gamma_N=\gamma_S$, except for the sectoral allocations of labor and physical capital, and the output–capital ratio.

The necessary optimality conditions are:

$$\omega c_n^{\gamma_N-1}=\upsilon_1, \tag{18a}$$

$$(1-\omega)c_s^{\gamma_S-1}=\upsilon_1, \tag{18b}$$

$$\alpha_R(y/r)\upsilon_1+r^{\theta-1}a^{-\varepsilon}\upsilon_3=0, \tag{18c}$$

$$\upsilon_1\alpha_L(y/u)=\upsilon_2\beta_L(j/(1-u)), \tag{18d}$$

$$\upsilon_1\alpha_K(y/v)=\upsilon_2\beta_K(j/(1-v)), \tag{18e}$$

$$\alpha_K(y/k)-\delta_K^*+(\upsilon_2/\upsilon_1)\beta_K(j/k)=\rho-(\dot{\upsilon}_1/\upsilon_1), \tag{18f}$$

$$\beta_A(j/a)-\delta_A^*+(\upsilon_1/\upsilon_2)\alpha_A(y/a)-(\upsilon_3/\upsilon_2)\varepsilon(a\theta)^{-1}r^\theta a^{-\varepsilon}=\rho-(\dot{\upsilon}_2/\upsilon_2), \tag{18g}$$

$$-(1-\omega)D\upsilon_3^{-1}-\delta_P^*=\rho-(\dot{\upsilon}_3/\upsilon_3), \tag{18h}$$

$$\lim_{t\to\infty}e^{-\rho t}\upsilon_1 k=0,\quad \lim_{t\to\infty}e^{-\rho t}\upsilon_2 a=0,\quad \lim_{t\to\infty}e^{-\rho t}\upsilon_3 P^*=0, \tag{18i}$$

where υ_1, υ_2, and υ_3 are the shadow values of capital, technology and pollution, respectively.

We note from (18a) and (18b) that along the Pareto-efficient paths, the weighted marginal utilities of consumption in both regions are the same. Moreover, (18a), (18b), and (18c) imply an efficient resource price which would equate the marginal global benefits of resource use (the weighted marginal utility of consumption in both regions times the marginal product of the resource) to the marginal pollution costs in the South (valued at the shadow price of pollution in the South). Also, (18d) and (18e) indicate a sectoral allocation rule for labor and capital such that productivities are equalized at the margin. Finally, (18f), (18g), and (18h) indicate how the globally efficient shadow values of k, a, and P^* will move over time. Once again, note that (18h) and the corresponding transversality condition in (18i) imply that the optimal shadow price of scaled pollution is constant.

The following system of equations indicate the steady state of the cooperative trade game where the efficient levels of the stationary variables are denoted by "$\breve{}$":

$$(\breve{y}/\breve{k})-(\breve{c}_n/\breve{k})-(\breve{p}^*\breve{r})\breve{k}^{-1}-\delta_K^*=0, \tag{19a}$$

$$(\breve{j}/\breve{a})-\delta_A^*=0, \tag{19b}$$

$$(1/\theta)\left(\breve{P}^*\breve{a}^\varepsilon\right)^{-1}\breve{r}^\theta-\delta_P^*=0, \tag{19c}$$

$$\omega\breve{c}_n^{\gamma_N-1}-(1-\omega)(\breve{p}^*\breve{r})^{\gamma_S-1}=0, \tag{19d}$$

$$\breve{v}-\alpha_K\beta_L\breve{u}[\alpha_K\beta_L\breve{u}+\alpha_L\beta_K(1-\breve{u})]^{-1}=0, \tag{19e}$$

$$\alpha_K(\breve{y}/\breve{k})-\delta_K^*+\beta_K\alpha_L(1-\breve{u})[\beta_L\breve{u}]^{-1}(\breve{y}/\breve{k})-\rho=0, \tag{19f}$$

$$\beta_A(\breve{j}/\breve{a})-\delta_A^*+(\alpha_A+(\varepsilon/\theta)\alpha_R)\beta_L\breve{u}[(1-\breve{u})\alpha_L]^{-1}(\breve{j}/\breve{a})-\rho=0, \tag{19g}$$

$$\alpha_R\breve{y}\omega\breve{c}_n^{\gamma_N-1}-(\rho+\delta_P^*)^{-1}\breve{a}^{-\varepsilon}(1-\omega)D\breve{r}^\theta=0. \tag{19h}$$

These equations are analogous to (16) and can be solved in a parallel way.

4. Simulations of the Model

We discretize the cooperative and non-cooperative games along the lines suggested by Mercenier and Michel (1994), which ensures the steady-state invariance between the continuous model and its discrete analog, and use genetic algorithms to approximate the steady state as well as the transient dynamics under various parameter configurations. The numerical procedures are described in detail in an appendix available from the authors on request.

Numerical Parameters and Baseline Equilibria

Table 1 displays the set of benchmark parameter values used in the numerical simulations. Insofar as possible, the baseline parameter values are adapted from earlier calibration studies and are generally conventional. Production of both the final goods and the new technologies exhibit increasing returns to scale.[8] We assume that both regions have the same rate of time preference and intertemporal elasticity of substitution, of 0.04 and 0.67, respectively. Physical capital is assumed to depreciate at the conventional rate of 5%. Knowledge, on the other hand, depreciates at a slower rate of 1%, while the rate of depreciation of pollution is assumed to be 7%. Populations in both regions are assumed to grow at 1.5%. Information on pollution parameter values is sparse, and therefore we conduct some sensitivity analysis with alternative parameter values. Equal weights, $\omega = 0.5$, are assigned to both regions in the cooperative trade game.

These benchmark parameter values yield the growth factors: $g_Y = 1.710$, $g_A = 2.105$, $g_p = -0.355$, and $g_R = 0.033$, implying a per capita growth rate of output, capital, and consumption of around 1.07%. Also, the benchmark equilibrium is characterized by an increasing resource extraction and a declining pollution in the South. Table 2b reports the total discounted North, South, and global welfares. The equilibrium values of other key variables are given in Table 2a.

Table 2b brings out a conflict between North and South with regard to the benefits from cooperation. By acting non-cooperatively North increases its welfare by 24.91%, while reducing South's welfare by 65.59%. The net effect of this unwillingness to cooperate is that the inefficiencies associated with non-cooperation impose a severe global welfare loss of 23.96%. In setting the resource price, South internalizes the local cost of pollution, as well as extracting monopoly rent from North. From a global perspective, to the extent that North also cares about the South's environment, resource prices would be inefficiently low because they would reflect only the local cost

Table 1. Benchmark Parameters

Production	$\phi_Y = 1.0$	$\alpha_K = 0.40$	$\alpha_L = 0.60$	$\alpha_A = 0.20$	$\alpha_R = 0.15$
Technology	$\phi_A = 1.0$	$\beta_K = 0.20$	$\beta_L = 0.50$	$\beta_A = 0.60$	
Pollution	$\delta_P = 0.07$	$\varepsilon = 0.20$	$\theta = 2.0$	$\tau = 0.0$	
Preferences	$\rho_N = 0.04$	$\rho_S = 0.04$	$\gamma_N = -0.5$	$\gamma_S = -0.5$	$D = 0.05$
Depreciation and population	$\delta_K = 0.05$	$\delta_A = 0.01$	$n_N = 0.015$	$n_S = 0.015$	

Table 2. Benchmark Equilibrium Values and Total Discounted Welfares

(a) Equilibrium values

Cooperation	$\breve{p}^*$	$\breve{r}$	$\breve{u}$	$\breve{v}$	$\breve{k}$	$\breve{P}^*$	$\breve{a}$	$\breve{c}_n$
	4.529	1.125	0.893	0.933	49.35	3.089	317.6	5.094
Non-cooperation	$\tilde{p}^*$	$\tilde{r}$	$\tilde{u}$	$\tilde{v}$	$\tilde{k}$	$\tilde{P}^*$	$\tilde{a}$	$\tilde{c}_n$
	1.275	1.823	0.899	0.937	54.67	8.225	298.1	9.035
%Δ Coop. to Non-coop.	–71.86	62.14	0.75	0.47	10.79	166.3	–6.16	77.37

(b) Total discounted welfares

	North		*South*		*Global*	
	Non-coop.	*Coop.*	*Non-coop.*	*Coop.*	*Non-coop.*	*Coop.*
	–24.66	–32.84	–63.86	–38.57	–88.53	–71.41
%Δ Coop. to Non-coop.	24.91		–65.59		–23.96	

of pollution. But this would be partly alleviated due to the exercise of monopoly power by the South, which therefore has some beneficial effects.

For its part, North chooses a resource allocation so as to maximize its own welfare. Resources that go to the production of final goods yield immediate higher consumption while those that are employed in the technology sector will yield a higher consumption only in the future. Since (i) delaying consumption is costly, (ii) resources that pollute South are employed only in the final goods production, and (iii) neither region internalizes the knowledge spillover, the non-cooperative equilibrium leads to an inefficiently small knowledge sector from a global perspective [298.1 vs 317.6]. As a result, non-cooperative behavior leads to an excess production of final goods, causing an over-accumulation of physical capital [54.7 vs 49.4] and an over-usage of resources [1.82 vs 1.13], the latter ultimately leading to an excessive level of pollution in the South [8.23 vs 3.09]. Next, we study the dynamic responses of regions to changes in some structural parameters.

Dynamic Responses to Structural Changes

Tables 3 to 5 and Figures 1 to 3 summarize the dynamic responses from the initial benchmark equilibrium, in response to various structural changes, namely (i) a 30% increase of productivity in the knowledge producing sector; (ii) an increase in knowledge diffusion from $\varepsilon = 0.20$ to $\varepsilon = 0.60$; (iii) a doubling in the resource damage rate from $\theta = 2.0$ to $\theta = 4.0$.

Productivity shocks in technology sector from $\varphi_A = 1.0$ to $\varphi_A = 1.30$ Being a nonscale model, all long-run growth rates remain unchanged. The productivity shock, however, generates transitional dynamics that have permanent level effects. Irrespective of the trading regime, the equilibrium levels of the scaled variables change significantly, leading to welfare improvements in both regions. The results are summarized in Tables 3a and 3b.[9]

The transition paths are illustrated in Figure 1. Since the technology sector does not employ the raw material, a productivity increase in that sector does not have an

Table 3. Productivity Shock Technology Sector

(a) Equilibrium values

Cooperation	$\breve{p}^*$	$\breve{r}$	$\breve{u}$	$\breve{v}$	$\breve{k}$	$\breve{P}^*$	$\breve{a}$	$\breve{c}_n$
	5.837	1.139	0.893	0.933	64.39	2.704	699.1	6.647
%Δ from benchmark	28.88	1.25	0.00	0.00	30.48	–12.46	120.1	30.48
Non-cooperation	$\tilde{p}^*$	$\tilde{r}$	$\tilde{u}$	$\tilde{v}$	$\tilde{k}$	$\tilde{P}^*$	$\tilde{a}$	$\tilde{c}_n$
	1.643	1.846	0.899	0.937	71.34	7.200	656.0	11.79
%Δ from benchmark	28.88	1.25	0.00	0.00	30.48	–12.46	120.1	30.48
%Δ Coop. to Non-coop.	–71.86	62.14	0.75	0.47	10.79	166.3	–6.16	77.37

(b) Total discounted welfares

	North		*South*		*Global*	
	Non-coop.	*Coop.*	*Non-coop.*	*Coop.*	*Non-coop.*	*Coop.*
	–23.97	–32.04	–62.89	–37.67	–86.87	–69.711
%Δ from benchmark	2.79	2.44	1.52	2.34	1.87	2.38
%Δ Coop. to Non-coop.	25.18		–66.97		–24.61	

Table 4. Increase in Knowledge Diffusion

(a) Equilibrium values

Cooperation	$\breve{p}^*$	$\breve{r}$	$\breve{u}$	$\breve{v}$	$\breve{k}$	$\breve{P}^*$	$\breve{a}$	$\breve{c}_n$
	2.045	3.594	0.879	0.924	70.58	2.619	442.5	7.352
%Δ from benchmark	–54.84	219.6	–1.49	–0.94	43.03	–15.22	39.32	44.33
Non-cooperation	$\tilde{p}^*$	$\tilde{r}$	$\tilde{u}$	$\tilde{v}$	$\tilde{k}$	$\tilde{P}^*$	$\tilde{a}$	$\tilde{c}_n$
	0.568	5.433	0.899	0.937	71.00	7.238	322.3	11.99
%Δ from benchmark	–55.42	198.0	–0.013	–0.008	29.87	–12.01	8.12	32.72
%Δ Coop. to Non-coop.	–72.22	51.15	2.27	1.42	0.59	176.4	–27.18	63.10

(b) Total discounted welfares

	North		*South*		*Global*	
	Non-coop.	*Coop.*	*Non-coop.*	*Coop.*	*Non-coop.*	*Coop.*
	–21.82	–29.19	–58.36	–34.54	–80.18	–63.73
%Δ from benchmark	11.50	11.14	8.62	10.43	9.42	10.76
%Δ Coop. to Non-coop.	25.22		–68.94		–25.81	

immediate direct simulating effect on the demand for the resource; rather its effect is indirect and occurs over time. On impact, the enhanced productivity in the technology sector induces North to shift both labor and capital to that technology. Under cooperation, since the efficient resource price reflects the benefits of pollution abatement from knowledge accumulation, it rises slightly to discourage production of the final goods, thereby accommodating the sectoral reallocation of labor and capital. Under non-cooperation, however, pollution costs are only internalized by the South while the

Table 5. Increase in Resource Damage Rate

(a) Equilibrium values

Cooperation	$\breve{p}^*$	$\breve{r}$	$\breve{u}$	$\breve{v}$	$\breve{k}$	$\breve{P}^*$	$\breve{a}$	$\breve{c}_n$
	4.644	1.061	0.896	0.935	47.619	1.568	295.6	4.927
%Δ from benchmark	2.53	–5.67	0.38	0.24	–3.51	–49.23	–6.95	–3.28
Non-cooperation	$\tilde{p}^*$	$\tilde{r}$	$\tilde{u}$	$\tilde{v}$	$\tilde{k}$	$\tilde{P}^*$	$\tilde{a}$	$\tilde{c}_n$
	1.566	1.362	0.899	0.937	50.224	4.290	286.3	8.293
%Δ from benchmark	22.86	–25.30	0.001	0.0003	–8.14	–47.84	–3.95	–8.22
%Δ Coop. to Non-coop.	–66.28	28.40	0.38	0.24	5.47	173.56	–3.14	68.32

(b) Total discounted welfares

	North		*South*		*Global*	
	Non-coop.	*Coop.*	*Non-coop.*	*Coop.*	*Non-coop.*	*Coop.*
	–25.44	–33.04	–60.88	–37.09	–86.33	–70.14
%Δ from benchmark	–3.16	–0.61	4.66	3.82	2.49	1.79
%Δ Coop. to Non-coop.	23.01		–64.14		–23.08	

benefits of knowledge spillovers are altogether discounted. Hence, the shift in labor and capital to technology sector is smaller. Nonetheless, the demand for resources fall, leading the South to lower the resource price for a short period of time after which resource use rapidly increases and peaks. In both instances, knowledge accumulates rapidly, while the capital stock actually declines slightly for a brief period because of the higher productivity and the increased employment of labor and capital in the technology sector.

Over time, as knowledge is accumulated in the North, the productivity of capital is enhanced and it too is accumulated. The expansion of final output in the North stimulates the demand for resources. This induces South to start raising its price. However, its effect is to less than offset the rising demand under cooperation, so that the rate of resource extraction keeps increasing at a steady, though declining rate. Under non-cooperation, however, the effect of increasing price is to more than offset the rising demand, so that the rate of resource extraction, after the brief initial increase and peak, declines at a steady, though declining rate.

The increase in capital accumulation and final output induces the North to gradually shift its capital and labor back toward the production of final output, ultimately restoring the initial allocation. The initial increase in resource extraction under non-cooperation slightly increases the level of pollution in the South. However, this declines after a short period due to the decline in the rate of resource extraction plus the improved abatement due to the higher stock of technology. In the long run, pollution in the South declines substantially by about 12.46%. The important point to observe is that a technological improvement in North's knowledge sector leads to a long-run reduction in pollution, and therefore an improvement in South's welfare, albeit modest.

Increase in the knowledge diffusion ε *from* 0.20 *to* 0.60 This form of technological increase does have implications for the long-run growth rates, raising the growth factors of final output, g_Y, technology, g_A, and resource, g_R, to 1.833, 2.166, and 0.442,

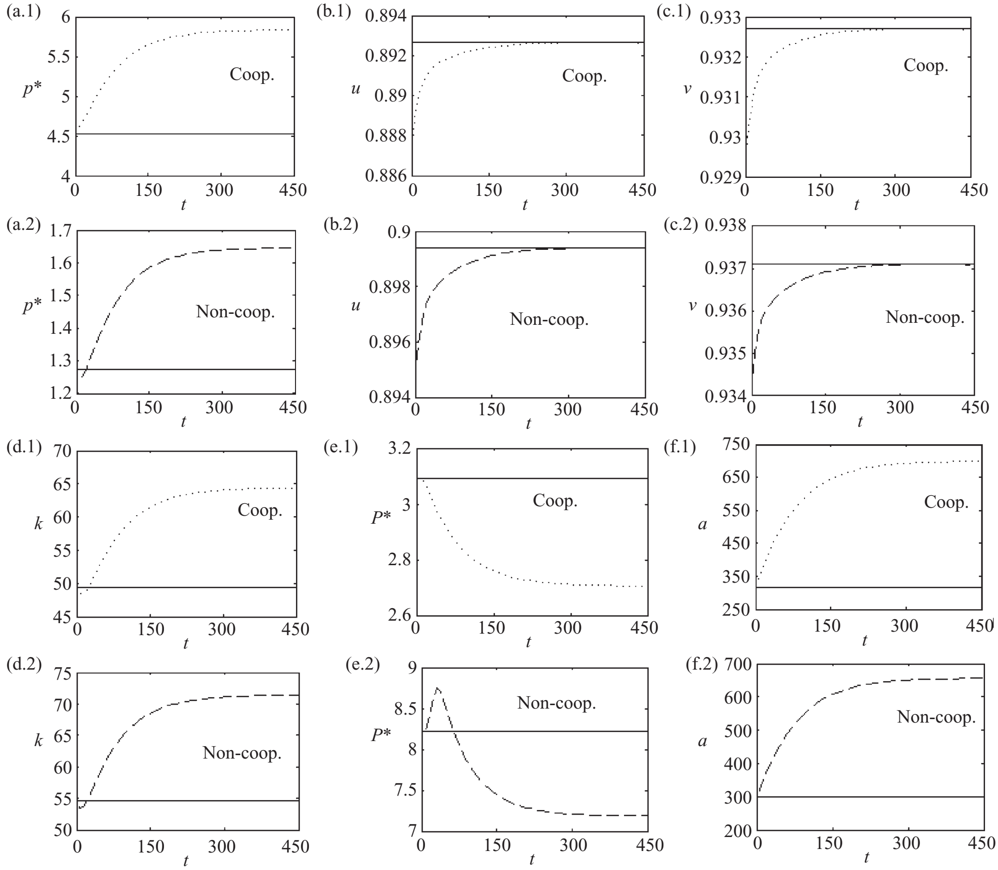

Figure 1. Transitional Dynamics in Response to a Productivity Shock in the Technology Sector (horizontal lines denote initial benchmark values)

respectively, while reducing the growth factor of pollution, g_P, to –0.416. From Table 4b we see that this leads to a 9.42% increase in global welfare with uncoordinated trading policies, and an even larger increase (10.76%) under cooperation, attesting to the importance of access to knowledge. The implication is that returns from investment in knowledge to North are not only in the form of improved productivity there, but also in the form of lower resource prices due now to the higher rate of pollution abatement in the South. Moreover, with the increased South's capacity to absorb technology, pollution will be less of a drag on growth in North. The equilibrium values with the higher knowledge spillover rate are reported in Table 4a.

First, note the rise in the optimal long-run resource/capital and resource/knowledge ratios under both cooperative and non-cooperative modes of trade. This will be true because a higher rate of knowledge diffusion will reduce the long-run cost of pollution and thereby the supply price of resources, and make the increased use of resources for any given level of physical capital and knowledge optimal. Also noteworthy from Figure 2 and Table 4a is the increase in the stationary physical capital and knowledge stocks and the shares of labor and physical capital in the knowledge sector.[10] Higher physical capital due to lower price of resources allows North to shift resources to the knowledge sector, increasing knowledge stock. Finally, observe the fall in the pollution

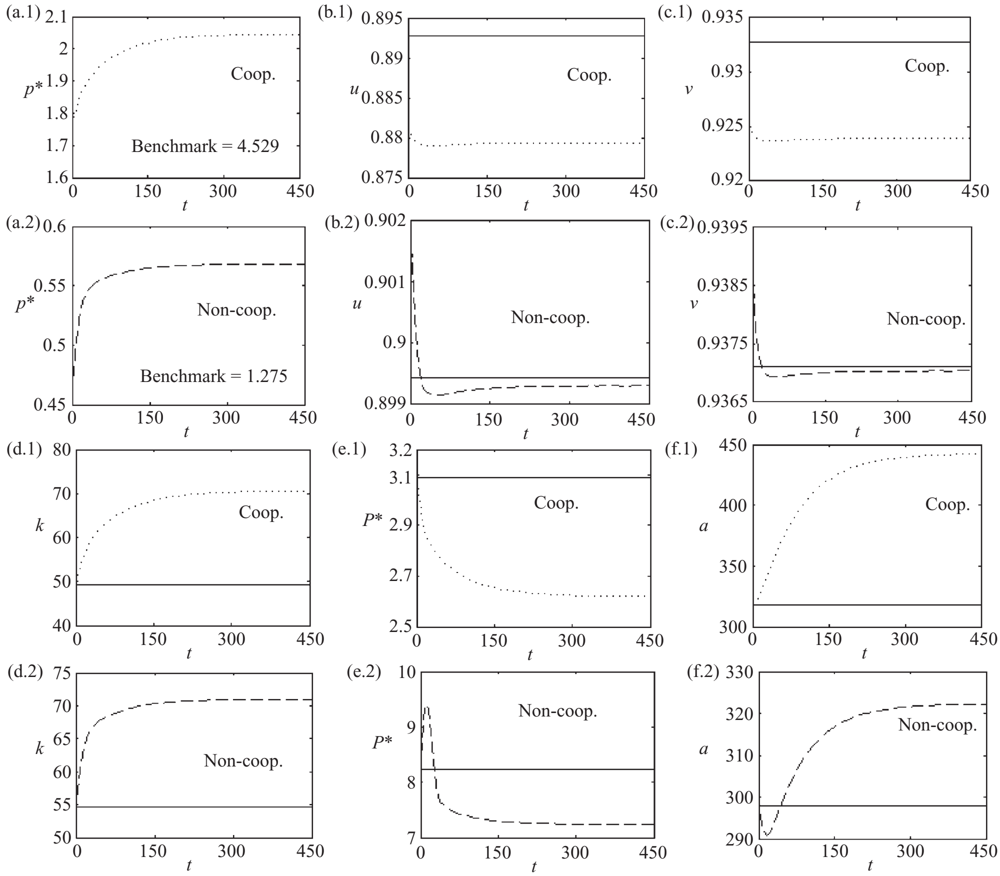

Figure 2. Transitional Dynamics in Response to Increased Knowledge Diffusion (horizontal lines denote initial benchmark values)

level. The marginal reduction in the pollution level due to higher knowledge stock outweighs the incremental increase due to a higher resource use so that the overall long-run pollution level will fall.

As for the dynamic adjustments, Figure 2 shows that with higher knowledge spillovers, the marginal cost of pollution falls, thus inducing South to instantly reduce the price for the resource, to which North's immediate response is to increase its usage. In the short run, the lower resource price enables North to accumulate more physical capital, which under non-cooperation, causes North to shift resources to the production of final output. This causes a temporary decline in level of technology, which, however, is reversed as the physical capital is accumulated and the productivity of knowledge is enhanced. Under cooperation, since North internalizes the knowledge spillovers, resources are shifted to the technology sector.

Over time, as knowledge is accumulated in the North, the productivity of capital is enhanced and it too is accumulated. The expansion of final output in the North further stimulates the demand for resources and this induces South to raise its price. Under cooperation, the increase in demand more than offsets the rise in price so that the rate of resource extraction keeps increasing at a steady, though declining, rate. Under non-cooperation, on the other hand, the effect of increasing price is to more than offset

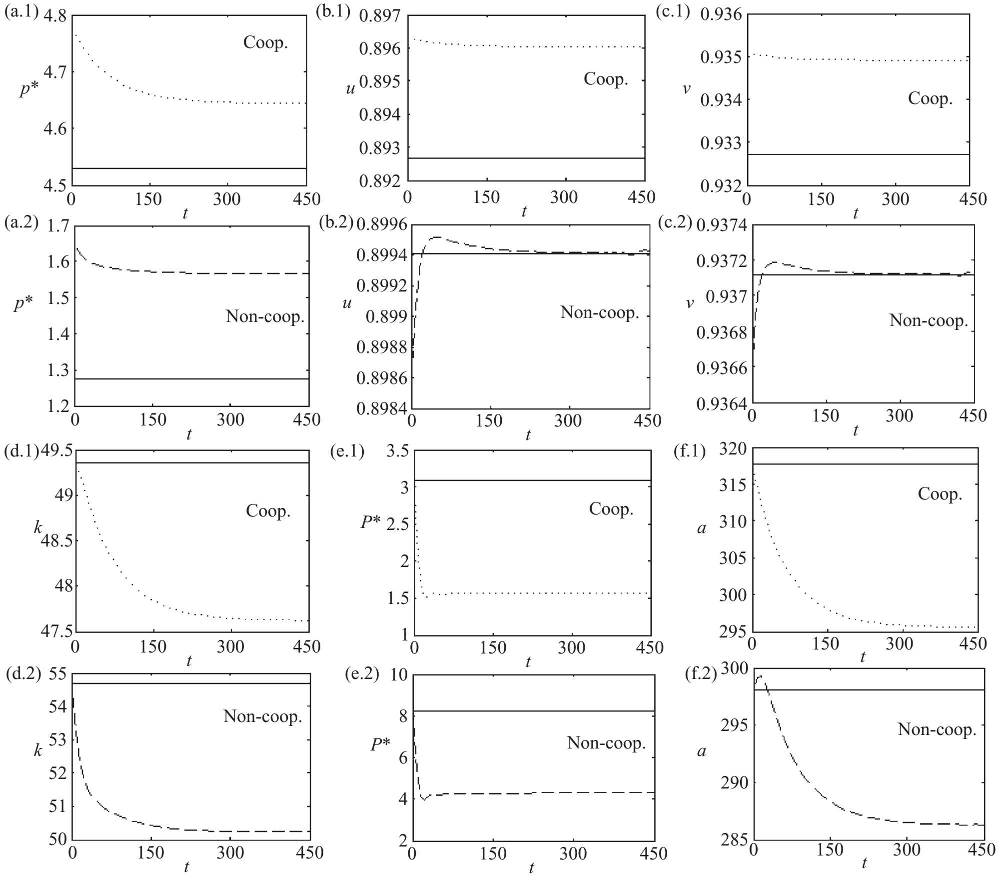

Figure 3. Transitional Dynamics in Response to Increased Resource Damage Rate (horizontal lines denote initial benchmark values)

the rising demand, so that the rate of resource extraction, after the initial instant increase, declines at a steady, though declining rate, leveling off at 198% of its benchmark value.

While the increase in resource extraction increases pollution in the South, the improvement in the diffusion of knowledge together with the increase in its stock has the opposite effect. Whereas the latter effect is dominant throughout under cooperation, under non-cooperation, the former initially dominates to give in, eventually, to the latter. Ultimately, the level of pollution declines by 15.22% and 12.01% under cooperation and non-cooperation, respectively.

Increase in resource damage rate θ from 2.0 *to* 4.0 As far as balanced growth factors are concerned, the most notable effect is on g_R which falls from 0.033 to 0.017. The other growth factors, g_Y, g_A, and g_P all decrease slightly, namely to 1.705, 2.103, and –0.353, respectively.

The new equilibrium values and the associated welfare are displayed in Tables 5a and 5b. Notice that in contrast to a favorable productivity shock in the final good sector in the North or to an increase in knowledge diffusion in the South the welfare effects are quite modest. What is more surprising is that North would suffer from such an increase in the potential damage to South's environment while South would be a beneficiary regardless of the trading regime. This could be explained by noting from Tables 5a and 5b that consumption in both regions falls but pollution is reduced drastically thereby causing a slight improvement in South's welfare. When resource extraction becomes more harmful to South's environment, the long-run marginal cost of pollution rises leading South to increase the resource price. With higher long-run resource prices, North cuts production of both the final good and the technology. Also, since the resource is relatively more expensive now, the final good is produced with relatively less resource and more capital and labor that become available from the diminished technology sector. While the decreased resource use causes pollution in the South to decline, decreased technology has the opposite effect. But the former dominates resulting in lower pollution in the South. With cooperation, as pollution is globally internalized, the efficient resource price rises less so that these effects on welfares are less pronounced. While North's welfare deteriorates less, South's welfare improves less, too.

The dynamic adjustments are illustrated in Figure 3. As the order of environmental damage increases, the marginal cost of pollution rises. This induces South to immediately increase the price for the resource, to which North's instant response is to decrease its usage, causing the rate of physical capital accumulation to decline. Under non-cooperation, as only South internalizes the increased pollution costs, relative to the benchmark non-cooperative scenario, the rise in the resource price is much sharper. Increased resource price and decreased productivity in the final good sector also induces North to shift resources toward the production of knowledge in the short run. This causes a temporary increase in level of technology, which, however, is reversed as the physical capital is reduced and the productivity of knowledge declines. Under cooperation, the resource price rises to reflect the now increased global cost of the resource extraction, thereby inducing North to shift resources away from the production of knowledge in the short run to substitute for the resource in the production of the final good.

Under non-cooperation, decreased resource use and initial increase in technology causes pollution to decrease rapidly. Under cooperation, while the decline in resource extraction decreases pollution in the South, the decrease in the stock of knowledge has the opposite effect. However, the former effect dominates and since the decline in knowledge is in fact only modest, whereas the decline in resource extraction occurs immediately, the net effect is a rapid decline in the level of pollution in the South. As a result of declining resource demand and pollution, the resource price starts decreasing. This causes the resource extraction to start picking up under non-cooperation. However, the increase in price is less than proportionate under cooperation, so that the resource demand keeps declining. Eventually, resource extraction levels off at a level 5.67% below its benchmark value under cooperation and 25.30% below its benchmark value under non-cooperation.

With cooperation, the decline in pollution due to decreasing resource extraction keeps dominating the increase in pollution due to declining stock of knowledge, so that the level of pollution in the South keeps decreasing. Under non-cooperation, pollution depreciates more than the increase in pollution due to increasing resource extraction and declining stock of knowledge, so that the level of pollution in the South keeps decreasing under non-cooperation as well. Eventually, pollution levels off at a level around 49.23% below its initial value under cooperation and around 47.84% below its initial value under non-cooperation. The change in the level of pollution is more significant in the cooperative game since the positive effect of knowledge spillovers on pollution accumulation is internalized in both regions.

5. Conclusion

To highlight the potential strategic asymmetries in the world trade, the paper has constructed a dynamic game between the North and the South. South causes local pollution while extracting a resource that it sells to North at a monopoly price. North uses the resource, together with capital, labor, and knowledge, to produce a final good to consume, to invest, and to sell to South at a fixed world price. North's growth is endogenously generated by the technology sector that produces knowledge which flows freely to South to help abate pollution from resource extraction there.

North chooses a resource allocation with a view to maximizing own welfare, ignoring the deleterious effects of its policies on South's environment. South, on the other hand, sets the resource price to reflect the local cost of pollution as well as to extract monopoly rent from North, neglecting the effects of its policy on North's growth. From a global perspective, resource prices are inefficiently low because they only reflect the local cost of pollution. This, however, is partly alleviated by South's monopoly power.

Moreover, while the final goods can be immediately consumed, labor and capital allocated to the technology sector will bring, via increased productivity, higher consumption only in the future. Given that delaying consumption is costly to North, that natural resources are employed only in the final goods production, and that neither region internalizes the knowledge spillovers, all lead to an inefficiently small knowledge sector from a global perspective. An excess production of the final goods causes an over-accumulation of physical capital and an over-use of resources, the latter ultimately leading to an excessive level of pollution in the South. These results are replicated under various parameter configurations.

Further, although the pollution we consider is local in nature, it has global ramifications for growth. All else being the same, an increased rate of knowledge diffusion in the South makes resource extraction less costly, leading to lower prices and thus faster accumulation of both physical capital and knowledge in the North. Conversely, North's growth can be checked if resource extraction creates more damage to South's environment. Trade couples the regions and acts as a conduit for the local changes to be transmitted to each other.

Owing to the inefficiencies that accompany the non-cooperative mode of trade, global welfare is substantially lower under non-cooperation than it is under cooperation. Also, a regime switch from a non-cooperative to a cooperative trade regime is always beneficial to South and harmful to North. Consequently, not only is North unwilling to cooperate, but also the inefficiencies that arise from such a reluctance are severe.

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Notes

1. Early studies analyzing resource policy in a strategic framework include Levhari and Mirman (1980) and Dasgupta (1982). Many studies use dynamic game theory to focus on various aspects of environmental issues such as joint exploitation of natural resources (Benhabib and Radner, 1992; Sorger, 1998) and transboundary pollution (Chander and Tulkens, 1992; van der Ploeg and de Zeeuw, 1992, 1994; Dockner and Long, 1993; Hoel, 1997).
2. Since the focus of the paper is to explore how various sources of inefficiencies interact to distort growth in a strategic framework, not the credibility of the optimal regional policies, we focus on open-loop strategies. Unless a quadratic–linear framework is adopted at the outset, numerical approximation of feedback Nash policies is fraught with difficulties. It is also obvious that the quadratic–linear framework is not suitable for modeling permanent growth. Karp (1984) and Batabyal and Beladi (2006) focus on issues of credibility within the context of a differential Stackelberg game.

3. It could also be endowed with a fixed supply of capital, so that its production function is of the form $R(t) = bL_S(t)\bar{K}_S$, where $\bar{K}_S$ denotes the fixed capital domiciled South.
4. That is, the population growth rate in the South is greater than or equal to the growth rate of the demand for the resource by the North.
5. This dichotomy in the technologies of North and South is pretty standard and serves to sharpen the analysis; see e.g. Galor (1986).
6. Thus, pollution is a "joint output" with resources in the South, increasing with its extraction.
7. See Eicher and Turnovsky (1999).
8. Production elasticities in the production of final output are well documented. However, much less empirical literature exists with respect to the production function for knowledge, especially if separate elasticities for labor, capital, and technology are required. Our parametrization employs the assumption that the production function for knowledge is relatively intensive in knowledge.
9. A comparable productivity increase in the final goods sector (discussed in an expanded version of this paper), generates a larger increase in the equilibrium levels, leading to larger welfare gains.
10. Because the benchmark equilibrium value of p^* and the new equilibrium differ significantly in magnitude, the benchmark equilibrium value is not drawn in Figures 2a.1 and 2a.2 to make the dynamics visible.