Economic Growth, Trade, and Environmental Quality in a Two-region World Economy*

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Abstract

This paper examines the 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, the North produces manufactured goods by employing labor, capital and a natural resource that it imports from the South. The 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 externalities. Cooperative trade policies are efficient and yet do not benefit the North. Both regions gain from improved productivity in the North and faster knowledge diffusion to the South regardless of the trading regime.

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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 of this asymmetric relationship that exists in the world economy, 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 consumption purposes, in return for the natural resource.

One of the important aspects of the world trading relationship that we envision is that the decisions of both regions potentially involve externalities that they are likely to impose. First, the extraction of the resource is likely to cause significant environment damage that may long persist, or that may even be irreversible. 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 production decisions. 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 with the North. 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 South trade non-cooperatively. Chichilnisky (1993,1994) emphasize ill-defined property rights over South's resources which gives rise to overexploitation 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, a large number of studies inquire the feasibility of sustained economic growth when environment acts as a natural constraint (e.g., Gradus and Smulders, 1993; Bovenberg and Smulders, 1995, 1996; Musu, 1996, Eliasson and Turnovsky, 2004). These studies, however, either ignore trade relationships between regions or assume that they are identical, (e.g., Hettich, 2000).

In this study, 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. Final output, which requires the use of the natural resource as an essential input, also uses labor, physical capital, and knowledge (technology), as productive inputs. Knowledge, which is produced in a second sector, does not require the natural resource as a productive input. Both productive 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 formal analytical solution and characterize the equilibrium dynamics. Then, the dynamic responses to various structural changes are analyzed and compared with the efficient paths. Specifically, we consider (i) a thirty percent increase of productivity in the final output sector; (ii) a thirty percent increase of productivity in the knowledge producing sector; (iii) a tripling in the applicability of knowledge to pollution reduction in the South and (iv) a doubling in the environmental damage rate of the natural resource.

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[1] Earlier studies analyzing resource policy in a strategic framework include Levhari and Mirman (1980) and Dasgupta (1982). A large number of 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 (Dockner and Long, 1993; Chander and Tulkens, 1992; van der Ploeg and de Zeeuw, 1992 and 1994; Benchekroun and Long, 1998; Hoel, 1997).

Due 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 is 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, to the extent that 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.

The balance of the paper is as follows. Section 2 lays out the model. Analytical solutions and equilibrium dynamics are studied in Section 3. Numerical simulations of the dynamic responses to various structural changes are discussed and compared with the efficient paths in Section 4. Section 5 concludes, while technical details of the numerical methods employed are summarized in the Appendix.

2. The Model

2.1. 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*, in accordance with a Cobb-Douglas production function:

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

where ϕ_Y is an exogenous technological shift parameter, $0 < \alpha_i < 1$, (i = *A*, *L*, *K*, *R*) are the productive elasticities, *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. The new technologies accumulate at a rate, *J*, while the stock of existing knowledge depreciates at a constant rate, δ_A. Thus the state of technology evolves according to:

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

where ϕ_A denotes an exogenous technological shift factor and $0 < \beta_i < 1$, (i = *A*, *L*, *K*) are the 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 price. 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,

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

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. [2]

[2] Early empirical evidence based on consumption data, strongly supported $s_N < 1$. More recent studies based on data drawn from financial markets obtains larger estimates for s_N, but still less than unity; see Guvenen (2005).

The South has no capital and hence does not invest. Its sole economic activity lies in resource extraction, which is done by employing labor alone in accordance with the constant returns to scale production function

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

We also assume that South's production is unconstrained by labor availability, $L_S(t)$.[3]

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:

$$\dot{P} = \frac{1}{\theta}\frac{R^\theta}{A^\varepsilon} - \delta_P P \tag{6}$$

where $\theta > 1$ measures the exponential 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 that the pollution decays naturally.[4]

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,

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

[3] 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. Also, if it is assumed that the supply of labor in the South is perfectly elastic at a fixed real wage $w(t)$ in terms of the industrial good, the nature of the labor force coupled with the CRS production function would then determine labor income per unit of raw material as $w(t) = b$. Competitive firms in the South will charge a price equal to the private marginal cost of resource extraction $w(t) = b$. The assumed social planner in the South levies an export tax, not only to internalize the social cost of pollution, but also to extract monopoly profit from the North.

[4] Equation (6) models pollution as a "joint output" with resources in the South, increasing with its extraction.

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 (2002), 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.

2.2. 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

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

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. Pre-commitment 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 loses that are likely to ensue given a lack of commitment.

3. 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 in physical capital, *K*, they all grow at the same constant rate. Second, technology, *A*, the pollution stock in the South, *P*, raw materials, *R*, and the relative price, *p*, all converge to (different) constant rates. Third, we assume that the ratio of the positive marginal benefits of per capita consumption to the negative marginal benefits of pollution in the South remain constant.

Given these assumptions, to determine the respective balanced growth rates, we take logarithmic differentials of the production functions (2a), (2b), the pollution evolution function (6), and the term in square parentheses of the integrand of (7). After some algebraic manipulation, we obtain:

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

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

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

$$\hat{R} = \left[\frac{\varepsilon}{\theta} g_A + \frac{1}{\theta} g_P\right] n_N \equiv g_R n_N \quad (9d)$$

$$\hat{p} = \hat{C}_S - \hat{R} \equiv \left(g_Y - \frac{\varepsilon}{\theta}\left(\frac{\beta_L + \beta_K g_Y}{1-\beta_A}\right)\right) n_N \equiv g_p n_N \quad (9e)$$

where ^ denotes the steady-state growth rate 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) – (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 environmental damage tends to discourage resource extraction, while the latter has the opposite effect. Second, an increase in the growth rate of North's final output tends to raise the growth rate of knowledge and the growth rate 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

$$\operatorname{sgn}(\hat{P}) = \left[\gamma_S(g_Y - 1) + \tau\right]$$

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". In the case that North's per capita growth rate is zero, $g_Y = 1$, and pollution operates as a pure public bad, $\tau = 0$, the long-run pollution in the south is constant. If $\gamma_S < 0$, growth in the North implies a steady reduction of pollution in the South and vice versa, while given North's growth rate, the perceived privatization of pollution in the South ($\tau > 0$) generates a steady increase in pollution.

To discuss the transitional dynamics for the trade games, 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.[5] Now, we can re-write the scale-adjusted output, and the rates of technology, physical capital and pollution stock as:

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

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

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

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

3.1. 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:

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

subject to (10a) – (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:[6]

[5] See Eicher and Turnovsky (1999).

[6] The same optimality conditions are obtained if one performs the optimization with respect to the original variables and then transforms to the scale-adjusted quantities; see Eicher and Turnovsky (1999).

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

$$\lambda_1 \alpha_L \frac{y}{u} = \lambda_2 \beta_L \frac{j}{1-u} \tag{12b}$$

$$\lambda_1 \alpha_K \frac{y}{v} = \lambda_2 \beta_K \frac{j}{1-v} \tag{12c}$$

$$\alpha_R \frac{y}{r} = p^* \tag{12d}$$

$$\alpha_K \frac{y}{k} + \frac{\lambda_2}{\lambda_1} \beta_K \frac{j}{k} - \delta_K^* = \rho_n - \frac{\dot{\lambda}_1}{\lambda_1} \tag{12e}$$

$$\beta_A \frac{j}{a} + \frac{\lambda_1}{\lambda_2} \alpha_A \frac{y}{a} - \delta_A^* = \rho_n - \frac{\dot{\lambda}_2}{\lambda_2} \tag{12f}$$

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

where $\lambda_1, \ \lambda_2$ 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 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

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

From equations (10a), (10b), (12b) and (12c), the respective optimal shares of labor and capital in the final good production are $u = u\left(\lambda_1, \ \lambda_2, \ a, \ k\right)$ and $v = v\left(\lambda_1, \ \lambda_2, \ a, \ k\right)$, which can be shown to have the following properties:

$$\operatorname{sgn}\left(\partial u/\partial k\right)=\operatorname{sgn}\left(\alpha_L-\beta_L\right);\operatorname{sgn}\left(\partial v/\partial k\right)=\operatorname{sgn}\left(\alpha_K-\beta_K\right)$$

$$\operatorname{sgn}\left(\partial u/\partial a\right)=\operatorname{sgn}\left(\partial v/\partial a\right)=\operatorname{sgn}\left(\alpha_A-\beta_A\right)$$

Intuitively, 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 will therefore move toward the sector in which that input has the greater production elasticity (is more productive).

We turn now to South. 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

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

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:

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

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

$$-\left(\frac{D}{\mu_2}+\delta_P^*\right)=\rho_s-\frac{\dot{\mu}_2}{\mu_2} \tag{15c}$$

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

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

From equation (15a), South's optimal terms of trade must be so chosen that the sum of incremental benefits from consumption and physical capital equals the marginal cost of pollution. Notice 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 ~:

$$\frac{\tilde{y}}{\tilde{k}} - \frac{\tilde{c}_n}{\tilde{k}} - \frac{\tilde{p}^*\tilde{r}}{\tilde{k}} - \delta_K^* = 0 \tag{16a}$$

$$\frac{\tilde{j}}{\tilde{a}} - \delta_A^* = 0 \tag{16b}$$

$$\frac{1}{\theta}\frac{\tilde{r}^\theta}{\tilde{P}^*\tilde{a}^\varepsilon} - \delta_P^* = 0 \tag{16c}$$

$$\alpha_R \frac{\tilde{y}}{\tilde{r}} - \tilde{p}^* = 0 \tag{16d}$$

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

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

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

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

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 Eqs. (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 equations (16b) and (16c). We use the production function for the final good and equation (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 equation (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 $\tilde{p}^*$.

3.2. 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.

Written in terms of the scale-adjusted quantities, the Pareto efficient paths maximize the weighted sum of welfares

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

subject to (10a)-(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:

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

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

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

$$\upsilon_1 \alpha_L \frac{y}{u} = \upsilon_2 \beta_L \frac{j}{1-u} \tag{18d}$$

$$\upsilon_1 \alpha_K \frac{y}{v} = \upsilon_2 \beta_K \frac{j}{1-v} \tag{18e}$$

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

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

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

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

where υ_1, υ_2, and υ_3 are the shadow values of aggregate physical 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, equations (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, equations (18d) and (18e), indicate a sectoral allocation rule for labor and capital such that productivities are equalized at the margin. Finally, equations (18f), (18g) and (18h) indicate how the globally efficient shadow values of *k*, *a*, and P^* will move over time. Once again, note that equation (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 ˇ

$$\frac{\breve{y}}{\breve{k}}-\frac{\breve{c}_n}{\breve{k}}-\frac{\breve{p}^*\breve{r}}{\breve{k}}-\delta_K^*=0 \tag{19a}$$

$$\frac{\breve{j}}{\breve{a}}-\delta_A^*=0 \tag{19b}$$

$$\frac{1}{\theta}\frac{\breve{r}^\theta}{\breve{P}^*\breve{a}^\varepsilon}-\delta_P^*=0 \tag{19c}$$

$$\breve{v}-\frac{\alpha_K\beta_L\breve{u}}{\alpha_K\beta_L\breve{u}+\alpha_L\beta_K(1-\breve{u})}=0 \tag{19d}$$

$$\alpha_K\frac{\breve{y}}{\breve{k}}-\delta_K^*+\frac{\beta_K\alpha_L(1-\breve{u})}{\beta_L\breve{u}}\frac{\breve{y}}{\breve{k}}-\rho=0 \tag{19e}$$

$$\beta_A\frac{\breve{j}}{\breve{a}}-\delta_A^*+\left(\alpha_A+(\varepsilon/\theta)\alpha_R\right)\frac{\beta_L\breve{u}}{(1-\breve{u})\alpha_L}\frac{\breve{j}}{\breve{a}}-\rho=0 \tag{19f}$$

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

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

Using (19b) one can get the equilibrium growth rate of knowledge, $\breve{j}/\breve{a}=\breve{J}/\breve{A}$. Then, equation (19f) can be used to determine the constant sectoral allocation of labor, $\breve{u}$.[7] Subsequently, equations (19d) and (19e) will give us the sectoral allocation of capital, $\breve{v}$, and the output-capital ratio, $\breve{y}/\breve{k}$, respectively. If $\omega=0.5$ and $\gamma_N=\gamma_S$, the equilibrium values of the rest of the variables are found as follows, otherwise one needs to employ a numerical method. Given $\tilde{y}/\tilde{k}$, the ratios of the South's consumption to capital, $\tilde{p}^*\tilde{r}/\tilde{k}$, and the North's consumption to capital, $\tilde{c}_n/\tilde{k}$, can be derived from (19a) using (19h). Having obtained $\tilde{y}/\tilde{k}$ and $\tilde{c}_n/\tilde{k}$, (19c) and (19g) determine the ratio $\tilde{P}^*/\tilde{k}^{\gamma_N}$. Given $\tilde{P}^*/\tilde{k}^{\gamma_N}$, $\tilde{u}$, and $\tilde{v}$, the ratio $\tilde{r}^\theta/\tilde{k}^{\gamma_S+\varepsilon\beta_K/(1-\beta_A)}$ can be obtained from equations (19b) and (19c). The production function for the final good and equation (19b) are used 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 $\tilde{v}$. Knowing $\tilde{k}$, $\tilde{a}$ and $\tilde{r}$ are derived from

[7] Note from Eq.s (19d) and (19f) that under cooperation higher fractions of capital and labor are allocated to the technology sector due to the fact that the marginal benefit from the accelerated knowledge accumulation from the North is now internalized in both regions.

equation (19b) 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 $\tilde{p}^*$.

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 (GAs) to approximate the steady state as well as the transient dynamics under various parameter configurations. The numerical procedures are described in detail in Appendix A.

4.1. Numerical Parameters and Baseline Equilibria

Table 1 displays the set of benchmark parameter values used in the numerical simulations. For the North, the baseline parameter values are adapted from earlier studies using calibration methods.[8]

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	$\delta_K = 0.05$	$\delta_A = 0.01$	$n_N = 0.015$	$n_S = 0.015$	

Production of both the final goods and the new technologies exhibit increasing returns to scale.[9] We assume that each region has the same rate of time preference and intertemporal elasticity

[8] See, for example, Lucas (1988), Ortigueira and Santos (1997), and Jones (1995).

[9] 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. For example, Adams (1990) and Caballero and Jaffee (1993) conduct thorough empirical investigations that are ultimately unsuccessful in reporting separate elasticities for labor and technology. Our parameterization employs the plausible assumption that the production function for knowledge is relatively intensive in knowledge.

of substitution, of 4 percent and 0.67, respectively.[10] Physical capital is assumed to depreciate at 5 percent, which is a common benchmark in the real business cycle literature; see e.g. Cooley (1995). Knowledge, on the other hand, depreciates at a slower rate of 1 percent, while the rate of depreciation of pollution is assumed to be 7 percent. Populations in both regions are assumed to grow at 1.5 percent. 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.

Table 2: Benchmark total discounted welfares

	North		South		Global	
	Non-coop.	Coop.	Non-coop.	Coop.	Non-coop.	Coop.
	-24.6611	-32.8438	-63.8642	-38.5686	-88.5253	-71.4124
Percent change from Coop. to Non-coop	24.91		-65.59		-23.96	

Table 3: Benchmark 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	49.350	3.089	317.629	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	54.673	8.225	298.057	9.035
Percent change from Coop. to Non-coop.	-71.86	62.14	0.75	0.47	10.79	166.25	-6.16	77.37

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 percent. Also, the benchmark equilibrium is characterized by an increasing resource extraction and a declining pollution in the South. Table 2 reports the total discounted North, South, and global welfares. The equilibrium values of other key variables are given in Table 3.

[10] As noted, the empirical evidence on the intertemporal elasticity of substitution is quite far-ranging. While early evidence drawn from consumption data obtained estimates of around 0.1 (Hall, 1988), subsequent studies based on financial data suggest a larger estimate. Our value of 0.67 is consistent with the value proposed by Guvenen (2005). But we should note that estimates of unity and even greater have been obtained (Beaudry and van Wincoop, 1995).

Table 2 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 percent, while reducing South's welfare by 65.59 percent. 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 percent. 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 of pollution. But this would be partly alleviated due to the exercise of monopoly power by the South. Thus, insofar as North cares about South's environment, South's monopoly power 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. 317.5]. 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.

4.2. Dynamic Responses to Structural Changes

Tables 4-7 and Figures 1-4 summarize the dynamic responses from the initial benchmark equilibrium, in response to various structural changes, namely (i) a 30 percent increase of productivity in the final output sector; (ii) a 30 percent increase of productivity in the knowledge producing sector; (iii) an increase in knowledge diffusion from $\varepsilon = 0.20$ to $\varepsilon = 0.60$; (iv) a doubling in the resource damage rate from $\theta = 2.0$ to $\theta = 4.0$.

4.2.1. Productivity shocks in final output sector

Consider an increase in the productivity of the final good sector from $\phi_Y = 1$ to 1.30. Being a non-scale model, all long-run growth rates remain unaltered in the face of change in scale parameters such as ϕ_Y. The productivity shock, however, sets into motion transitional dynamics that have permanent level effects; irrespective of the trading regime, the equilibrium levels of the scaled variables change significantly, leading to substantial welfare improvements in both regions. The results are summarized in Tables 4a and 4b.

Table 4a: Equilibrium Values

Cooperation	$\breve{p}^*$	$\breve{r}$	$\breve{u}$	$\breve{v}$	$\breve{k}$	$\breve{P}^*$	$\breve{a}$	$\breve{c}_n$
	8.204	1.019	0.893	0.933	80.961	2.412	406.831	8.357
Percent change from benchmark	81.13	-9.43	0.00	0.00	64.05	-21.93	28.08	64.05
Non-cooperation	$\tilde{p}^*$	$\tilde{r}$	$\tilde{u}$	$\tilde{v}$	$\tilde{k}$	$\tilde{P}^*$	$\tilde{a}$	$\tilde{c}_n$
	2.309	1.652	0.899	0.937	89.693	6.422	381.762	14.822
Percent change from benchmark	81.13	-9.43	0.00	0.00	64.05	-21.93	28.08	64.05
Percent change from Coop to Non-coop.	-71.86	62.14	0.75	0.47	10.79	166.25	-6.16	77.37

Table 4b: Total discounted welfares

	North		South		Global	
	Non-coop.	Coop.	Non-coop.	Coop.	Non-coop.	Coop.
	-20.5603	-27.7307	-56.6510	-32.9034	-77.2113	-60.6341
Percent change from benchmark	16.63	15.57	11.29	14.69	12.78	15.09
Percent change from Coop to Non-coop.	25.86		-72.17		-27.34	

The paths of some key variables are plotted in Figures 1.a)-1.l). By and large, dynamic adjustments are fairly similar whether regions cooperate or not. One should take note, however, of the inefficiencies in the non-cooperative adjustments due largely to the discount on the true global benefits of knowledge and costs of pollution. As such, non-cooperative transient dynamics favor production and accumulation of the final good over knowledge and hence an inefficiently high usage of the resource and excessive pollution in the South.

The transitional dynamics may be explained as follows. The immediate effect of the productivity increase is to raise North's demand for all productive factors, including the resource, to which South's immediate response is to raise its price. It does so more than proportionately under cooperation, so that the net effect is an instant decline in its usage by the North. Relatively speaking, the globally efficient levels of the final good and pollution are smaller so that efficiency calls for a sharper hike in the resource price both to reflect the benefits from knowledge spillovers and also the costs of pollution. At the same time, the higher productivity in the final output sector induces North to shift both labor and capital toward that sector but again less so under cooperation.

As a result of the higher productivity in the final output sector and the reallocation of resources that it attracts, physical capital accumulates rapidly, while the production of knowledge actually declines slightly for a brief period. Under non-cooperation, immediate increase in resource demand in the North coupled with the initial decrease in the production of knowledge implies that pollution abatement in the South decreases, so that the level of pollution increases for a short period of time. Under cooperation, however, instant decrease in resource demand in the North offsets the effect of initial decline in technology production, so that the level of pollution immediately starts to decline.

Over time, as physical capital is accumulated in the North, the productivity of knowledge is enhanced and it too is accumulated. Finally, the increase in demand for the resource due to the continuing expansion in economic activity in the North induces the South to continue raising its price, the effect of which is to more than offset the rising demand, so that the rate of resource extraction continues to decline, albeit at a declining rate.

As a consequence of the declining resource extraction, accompanied by the (generally) expansion in technology, the level of pollution steadily declines and eventually levels off at a level approximately 21.93 percent below its initial level under both cooperative and non-cooperative trades. The important point to observe is that a thirty percent increase in productivity in North's final output sector leads to a substantial decline in pollution in the South.

4.2.2. Productivity shocks in technology sector

A thirty percent increase in the productivity of knowledge production does not change the long-run growth rates. Relative to a comparable productivity increase in the final goods sector, changes in the equilibrium levels are smaller, leading to more modest welfare gains; see Tables 5a and 5b. Once again, the percentage changes in equilibrium values from their respective benchmark values are equal.

Table 5a: 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	64.394	2.704	699.127	6.647
Percent change from benchmark	28.88	1.25	0.00	0.00	30.48	-12.46	120.11	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	71.339	7.200	656.048	11.789
Percent change from benchmark	28.88	1.25	0.00	0.00	30.48	-12.46	120.11	30.48
Percent change from Coop. to Non-coop.	-71.86	62.14	0.75	0.47	10.79	166.25	-6.16	77.37

Table 5b: Total discounted welfares						
	North		South		Global	
	Non-coop.	Coop.	Non-coop.	Coop.	Non-coop.	Coop.
	-23.9732	-32.0425	-62.8934	-37.6677	-86.8666	-69.7101
Percent change from Benchmark	2.79	2.44	1.52	2.34	1.87	2.38
Percent change from Coop to Non-coop.	25.18		-66.97		-24.61	

The dynamic transition paths are now illustrated in Figures 2.a)-2.l) and may be explained along the following lines. In contrast to a productivity increase in the final goods sector, higher productivity in the technology sector does not have an immediate direct simulating effect on the demand for the resource. Instead, its effect is more indirect.

On impact, North shifts both labor and capital toward the technology sector because of the increased productivity there. Under cooperation, since the efficient resource price reflects the benefits of pollution abatement from knowledge accumulation, it slightly rises to discourage production of the final goods and thereby accommodating the sectoral reallocation of labor and capital. Under non-cooperation, however, pollution costs are only internalized by the South while the benefits of knowledge spillovers are altogether discounted. Hence, the shift in labor and capital to technology sector is not as much. 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 allocation of labor and capital in the technology sector.

However, 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 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 percent. Again a technological improvement in the North, this time in the knowledge sector, leads to a long-run reduction in pollution, and therefore an improvement in South's welfare, albeit modest.

4.2.3. Increase in the Knowledge Diffusion

We now investigate the effects of an improvement in the diffusion of knowledge in the South as represented by an increase in 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 respectively, while reducing the growth factor of pollution, g_P, to -0.416. Observe from Table 6b the increase in regional welfares attendant with stronger technology diffusion. We see about 9.42 percent improvement in global welfare with uncoordinated trading policies 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 thanks 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 6a.

Table 6a: 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	70.584	2.619	442.524	7.352
Percent change from benchmark	-54.84	219.61	-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	71.001	7.238	322.253	11.991
Percent change from benchmark	-55.42	197.95	-0.013	-0.008	29.87	-12.01	8.12	32.72
Percent change from Coop. to Non-coop.	-72.22	51.15	2.27	1.42	0.59	176.35	-27.18	63.10

Table 6b: Total discounted welfares						
	North		South		Global	
	Non-coop.	Coop.	Non-coop.	Coop.	Non-coop.	Coop.
	-21.8239	-29.1857	-58.3580	-34.5445	-80.1819	-63.7302
Percent change from Benchmark	11.50	11.14	8.62	10.43	9.42	10.76
Percent change from Coop to Non-coop.	25.22		-68.94		-25.81	

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 Figures 3. c) –j) and Table 6a is the increase in the stationary physical capital and knowledge stocks and the shares of labor and physical capital in the knowledge sector. Higher physical capital due to lower price of resources allows North to shift resources to knowledge sector, increasing knowledge stock. Finally, observe the fall in the pollution 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, figures 3. a)-l) show 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. This induces South to raise its price. However, its effect is less than offset the rising demand under cooperation, so 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 initial instant increase, declines at a steady, though declining rate, leveling off at 197.95 percent 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 percent and 12.01 percent under cooperation and non-cooperation respectively.

4.2.4. Increase in resource damage rate

The final experiment doubles the order of environmental damage due to resource extraction from $\theta = 2.0$ to $\theta = 4.0$. 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 welfares are displayed in Tables 7a and 7b.

Table 7a: 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	295.551	4.927
Percent change 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	286.270	8.293
Percent change from benchmark	22.86	-25.30	0.001	0.0003	-8.14	-47.84	-3.95	-8.22
Percent change from Coop. to Non-coop.	-66.28	28.40	0.38	0.24	5.47	173.56	-3.14	68.32

Table 7b: Total discounted welfares						
	North		South		Global	
	Non-coop.	Coop.	Non-coop.	Coop.	Non-coop.	Coop.
	-25.4403	-33.0432	-60.8849	-37.0941	-86.3252	-70.1373
Percent change from Benchmark	-3.16	-0.61	4.66	3.82	2.49	1.79
Percent change from Coop to Non-coop.	23.01		-64.14		-23.08	

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 Table 7a and 7b 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 Figures 4.a)-l). When 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, 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 percent less than its benchmark value under cooperation and 25.30 percent less than its benchmark value under non-cooperation.

Under 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 percent of its initial value under cooperation and around 47.84 percent of 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.

Due 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 is severe.

The model can be extended in various directions. To inquire whether North's reluctance for cooperation would change, a local pollution may also be added to accompany production of the final goods in the North. As a drawback, however, not only would the state space enlarge, making computation costlier, worse yet, balanced growth paths may not exist at all. Also, to enhance the credibility of the optimal regional policies, feedback Nash equilibria can be adopted as the solution concept. However, unless a linear-quadratic framework is adopted at the outset, numerical approximation of feedback Nash policies is fraught with difficulties. A part of our ongoing research agenda is to develop computationally efficient numerical methods to approximate feedback Nash equilibria. Finally, this type of analysis carries important policy implications that are important to develop if natural resources are to be managed efficieintly.

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Appendix A: Numerical Approximation of the Model

In order to determine the open-loop Nash equilibria of the two-person differential trade game, two optimal control problems need to be solved simultaneously (Başar and Oldser, 1982). Our numerical solution strategy is first to transform the infinite horizon differential game into a finite horizon difference game using time aggregation as in Michel and Mercenier (1994). Then, GAs optimize each problem using asynchronous updating.

In the cooperative trade game, the strategic rivalry that exists in the non-cooperative trade game is eliminated by way of an "arbitration" whereby the "global fitness" as the weighted sum of each region's respective welfare (fitness) is maximized. The cooperative trade game is thus reduced to a typical control problem which can be solved by standard GA techniques (Krishnakumar and Goldberg, 1992 and Michalewicz, 1992).

A.1. Discretization

The discrete-time approximation of infinite horizon non-cooperative North/South trade model with steady state invariance is as follows.

North:

$$\max J_n = \sum_{h=0}^{H-1} \Delta_h \mu_h^N \left(\frac{1}{\gamma_N} c_n(t_h)^{\gamma_N} \right) + \frac{\mu_{H-1}^N}{\rho_n} G^N \left(k(t_H), a(t_H) \right)$$

subject to

$$k(t_{h+1}) - k(t_h) = \Delta_h \left(y(t_h) - c_n(t_h) - p^*(t_h) r(t_h) - \delta_K^* k(t_h) \right)$$

$$a(t_{h+1}) - a(t_h) = \Delta_h \left(\phi_A a(t_h)^{\beta_A} (1 - u(t_h))^{\beta_L} \left[(1 - v(t_h)) k(t_h) \right]^{\beta_K} - \delta_A^* a(t_h) \right)$$

$k(t_0)$ and $a(t_0)$ given.

South:

$$\max J_s = \sum_{h=0}^{H-1} \Delta_h \mu_h^S \left(\frac{1}{\gamma_S} c_s(t_h)^{\gamma_S} - DP^*(t_h) \right) + \frac{\mu_{H-1}^S}{\rho_s} G^S \left(k(t_H), P^*(t_H) \right)$$

subject to

$$k(t_{h+1}) - k(t_h) = \Delta_h \left(y(t_h) - c_N(t_h) - p^*(t_h) r(t_h) - \delta_K^* k(t_h) \right)$$

$$P^*(t_{h+1}) - P^*(t_h) = \Delta_h \left(\frac{1}{\theta} \frac{r(t_h)^\theta}{a(t_h)^\varepsilon} - \delta_P^* P^*(t_h) \right)$$

$k(t_0)$ and $P^*(t_0)$ given.

where H is the assumed terminal time when the stationary state is reached, Δ_h is a scalar factor that converts the continuous flow into stock increments, $\Delta_h = t_{h+1} - t_h$, and μ^j is the sequence of discount factors of the region $i = N,\ S$ for which the stationary solution of the discrete-time problem is equivalent to the corresponding continuous-time problem. These sequences are given by the following recursions:

$$\mu_h^N = \frac{\mu_{h-1}^N}{1 + \Delta_h \rho_n},\ \mu_0^N > 0 \text{ and } \mu_h^S = \frac{\mu_{h-1}^S}{1 + \Delta_h \rho_s},\ \mu_0^S > 0$$

The functions $G^j(.)$, $j = N,\ S$ denote the terminal values. The cooperative model is time aggregated in a similar fashion.

A.2. Genetic Algorithms for Non-cooperative Open-loop Dynamic Games

The trade games involve both equality and inequality constraints. The equalities are eliminated at the start by substitution. We penalize the remaining constraint violations by a large reduction in the fitness so as to remain within the feasible region.[11]

Each population, North and South, is randomly initialized and best performing policies are passed on to the other player (GA) via the computer shared memory. Then each GA breeds newer

[11] See Michalewicz (1992) for various GA approaches to handle linear constraints.

and fitter populations of candidate solutions separately in the light of the best-to-date responses that are updated in every ten thousand generations.

The following pseudo code shows the general outline of the algorithm for the two-region dynamic trade game:

procedure North GA;
begin
  randomly initialize $\text{Pop}_N(0)$**;**
  shared memory;
  synchronize;
  evaluate $\text{Pop}_N(0)$
  $z = 1$**;**
  repeat
    select $\text{Pop}_N(z)$ **from** $\text{Pop}_N(z-1)$**;**
    copy best to shared memory;
    synchronize if z **mod 10000 = 0;**
    crossover and mutate $\text{Pop}_N(z)$**;**
    evaluate $\text{Pop}_N(z)$**;**
    $z = z+1$**;**
  until (termination condition);
end;

procedure South GA;
begin
  randomly initialize $\text{Pop}_S(0)$**;**
  shared memory;
  synchronize;
  evaluate $\text{Pop}_S(0)$**;**
  $z = 1$**;**
  repeat
    select $\text{Pop}_S(z)$ **from** $\text{Pop}_S(z-1)$**;**
    copy best to shared memory;
    synchronize if z **mod 10000 = 0;**
    crossover and mutate $\text{Pop}_S(z)$**;**
    evaluate $\text{Pop}_S(z)$**;**
    $z = z+1$**;**
  until (termination condition);
end;

In each step of this algorithm, two GAs evolve a constant size population of potential solutions. The two GAs are separately evolved for ten thousand generations upon sharing their best to date responses. The synchronize statement in the above algorithm is a protocol whereby each party is to wait for the other side to update their respective best structures before proceeding with a new search. This approach reduces time complexity while at the same time ensuring the convergence to the global Nash equilibrium.

A.3. Genetic Algorithm for Cooperative Games

Generally speaking, for s control variables, T periods, and l potential solutions, a GA performs the following steps to optimize a control problem: (1) Randomly generate an initial potential solution set, (2) Evaluate the fitness value for a solution set of *sTl*, (3) Apply selection, crossover, and mutation operations to each set of solutions to reproduce a new population, (4) Repeat steps (1), (2) and (3) until computation is terminated according to a convergence criterion, (5) Choose the solution set *sT* based on the best fitness value from the current generations as the optimal solution set.

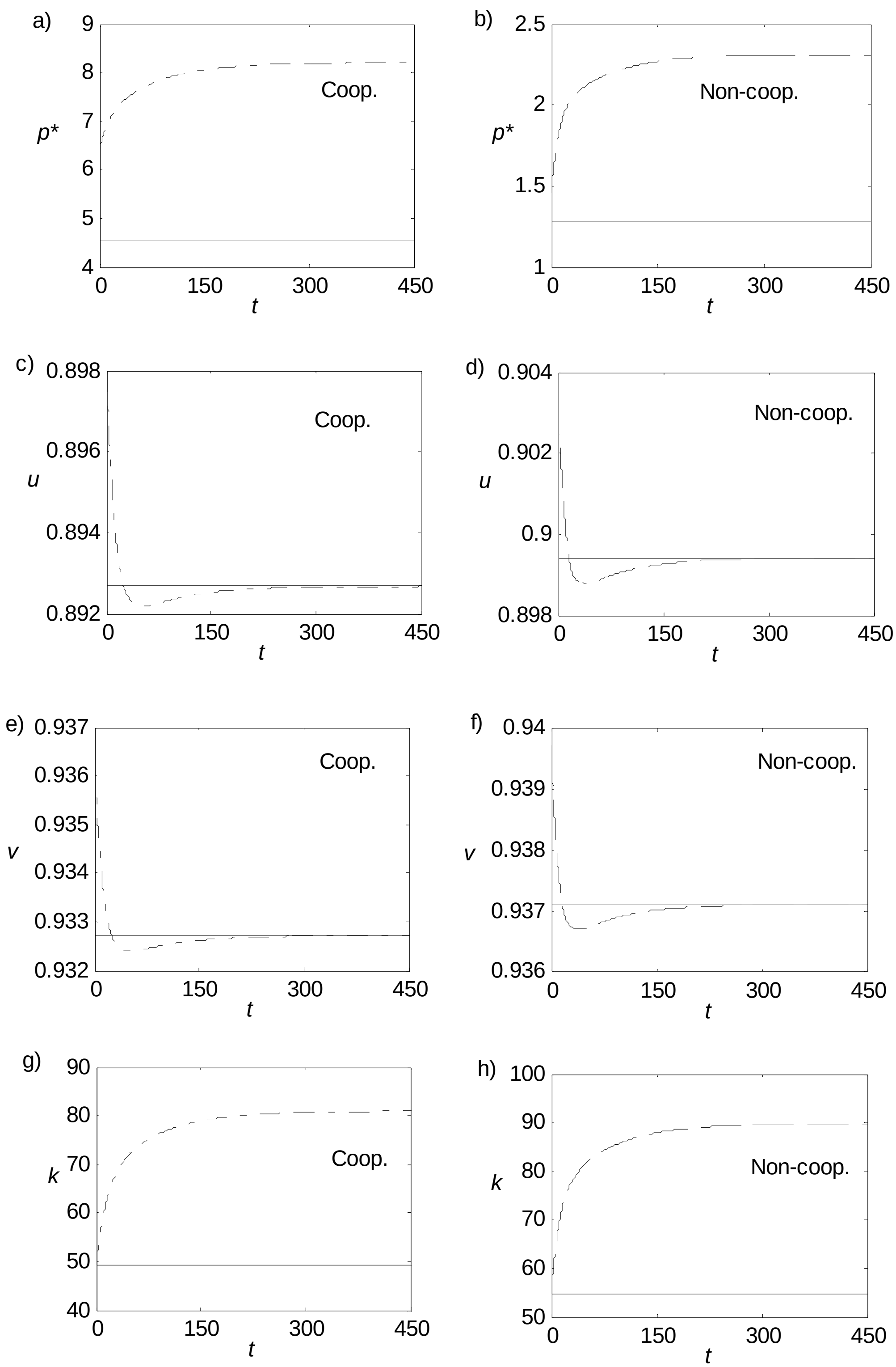
A.4. Genetic Algorithm Parameters

Since GAs work with constant-size populations of candidate solutions, GA searches are initialized from a number of points. Initialization routines may vary. We however start from randomly generated populations so as not to prejudice the convergence of the populations on the initial ones. Therefore, a randomly initialized GA is less prone to numerical instability that may be caused by initialization. For the GA parameters which might cause instability, we used the parameters chosen and studied on various optimization experiments by Grefenstette (1986). From the result of the experiments in the paper, the convergence is self evident. The termination conditions are specified beforehand as a certain number of iterations. We gradually increase the number of iterations until no further improvements are observed. In the time-aggregated model, we assume 31 periods (H=30) with a dense equally spaced gridding of the time horizon $T(t(H) = 450)$, which is sufficient to capture the convergence over time.

As for the genetic operators in the numerical experiments, we use the public domain GENESIS as a platform (Grefenstette, 1990) and modify the GENESIS codes as we need them. All experiments are run on an IBM RS/6000 running AIX 5.2. A typical run uses population size, j = 50, runs one million generations, crossover rate is 0.60 and mutation rate is 0.001. The selection strategy is elitist so that the best performing strategy in the population of survivors is retained. None of the results depends on the values of genetic operators other than run time by the choice of number of generations. For each parameter configuration, we have to implement two separate experiments. Hence, we are limited by the increased computational costs in our scope for a complete sensitivity analysis

Appendix B: Transitional Dynamics (Coop.: Cooperative; Non-coop.: Non-cooperative)

Figure 1. Transitional Dynamics in response to a productivity shock in the final good sector:



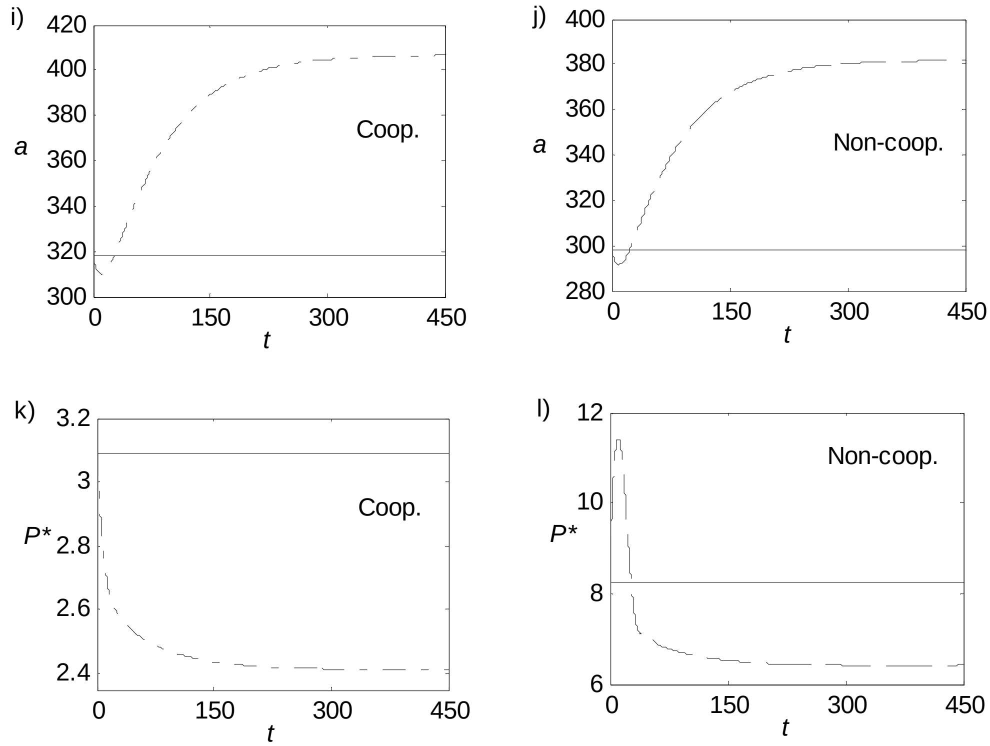
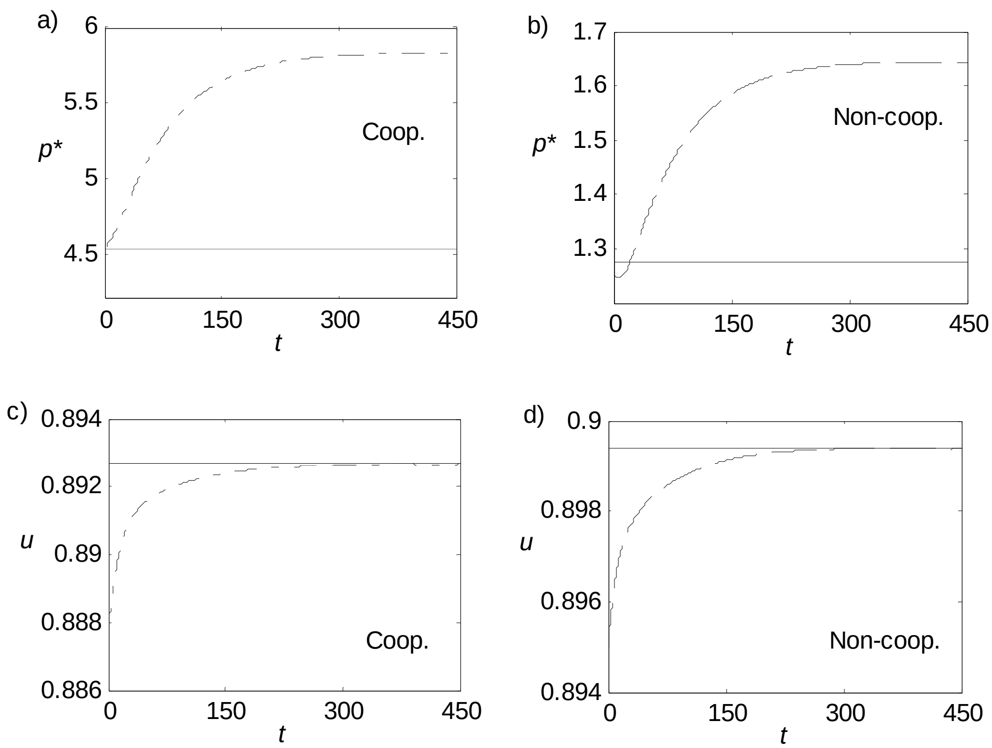


Figure 2. Transitional Dynamics in response to a productivity shock in the technology sector:



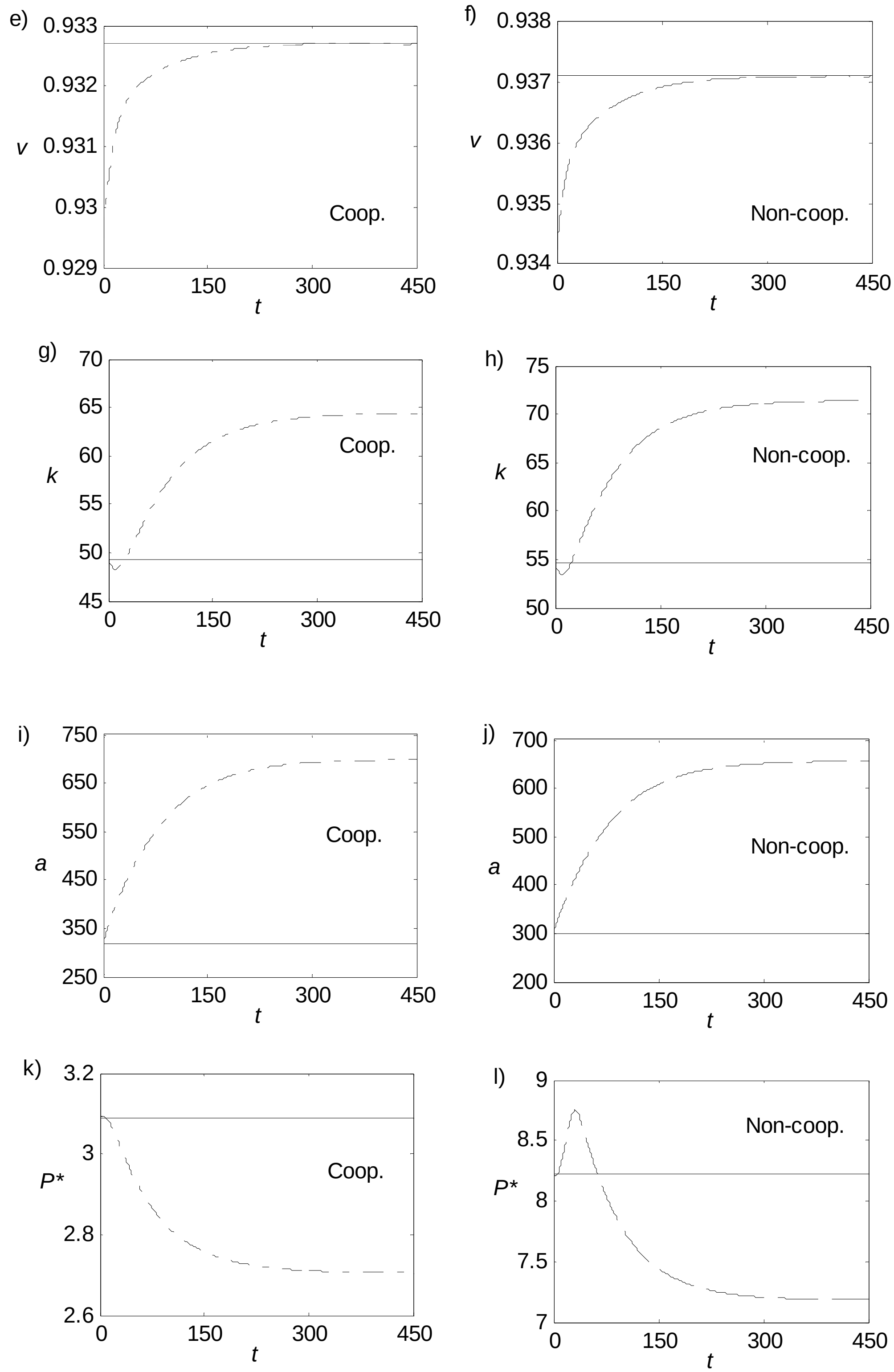
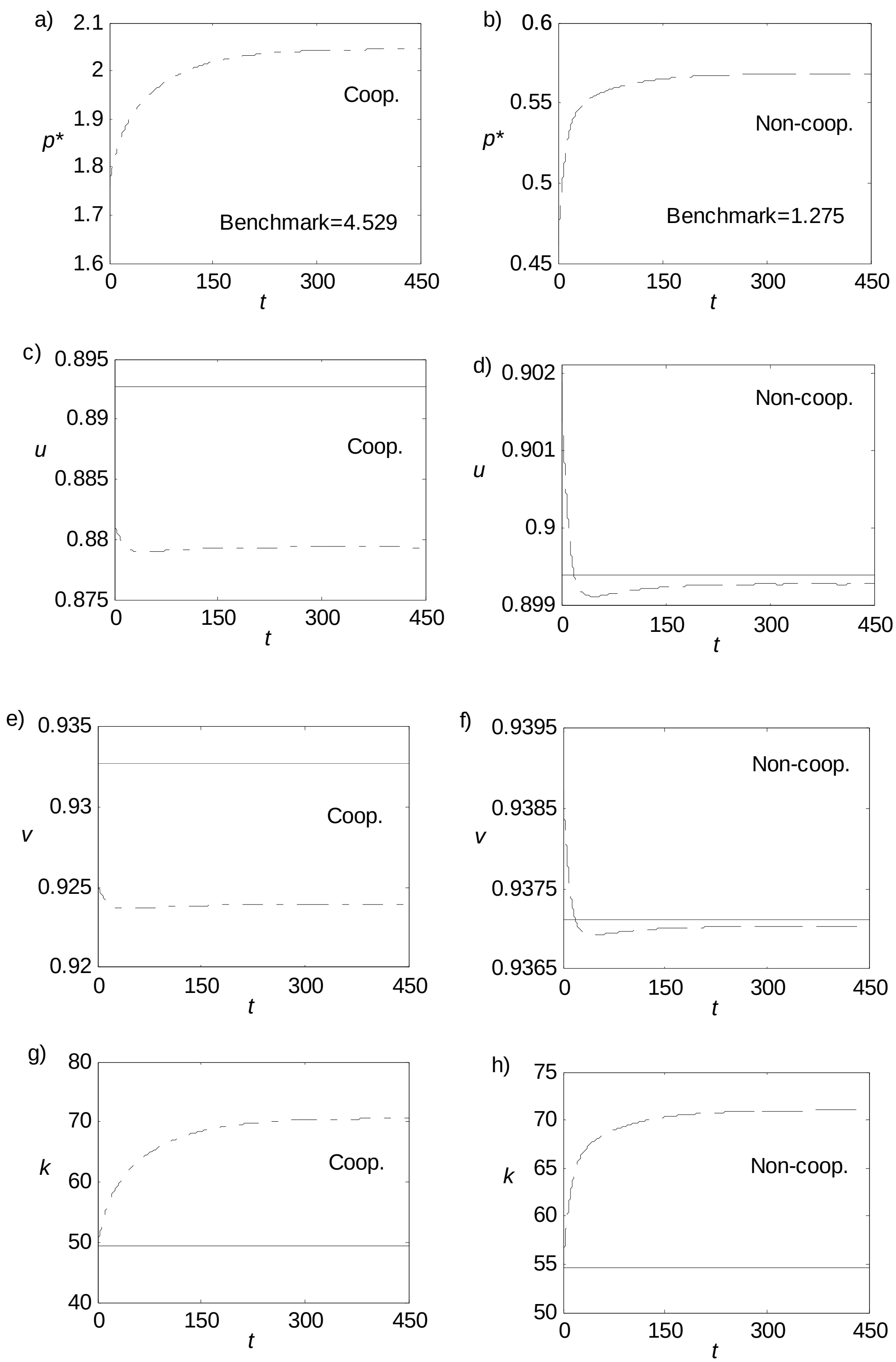

e)
0.933
0.932
v
0.931
0.93
0.929
Coop.
0
150
300
450
t
f)
0.938
0.937
v
0.936
0.935
0.934
Non-coop.
0
150
300
450
t
g)
70
65
60
k
55
50
45
Coop.
0
150
300
450
t
h)
75
70
65
k
60
55
50
Non-coop.
0
150
300
450
t
i)
750
650
550
a
450
350
250
Coop.
0
150
300
450
t
j)
700
600
500
a
400
300
200
Non-coop.
0
150
300
450
t
k)
3.2
3
P*
2.8
2.6
Coop.
0
150
300
450
t
l)
9
8.5
P*
8
7.5
7
Non-coop.
0
150
300
450
t

Figure 3. Transitional Dynamics in response to increased knowledge diffusion:[12]



[12] Because the benchmark equilibrium value of p^* and the new equilibrium differ significantly in magnitude, benchmark equilibrium value is not drawn in Figure 3.a) to make the dynamics visible.

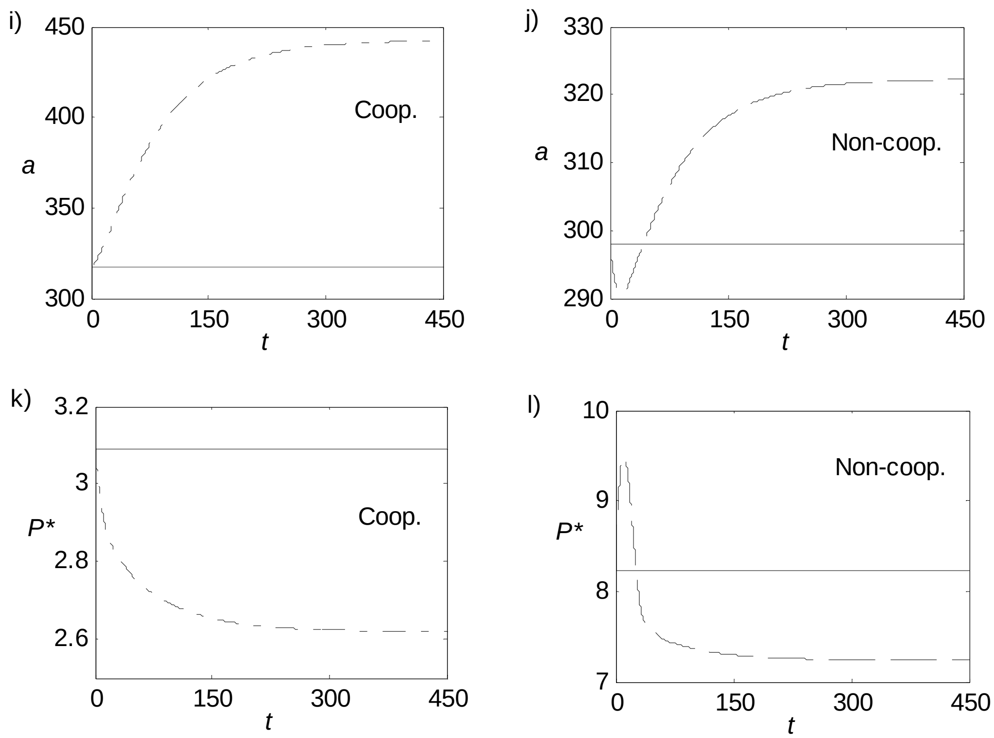
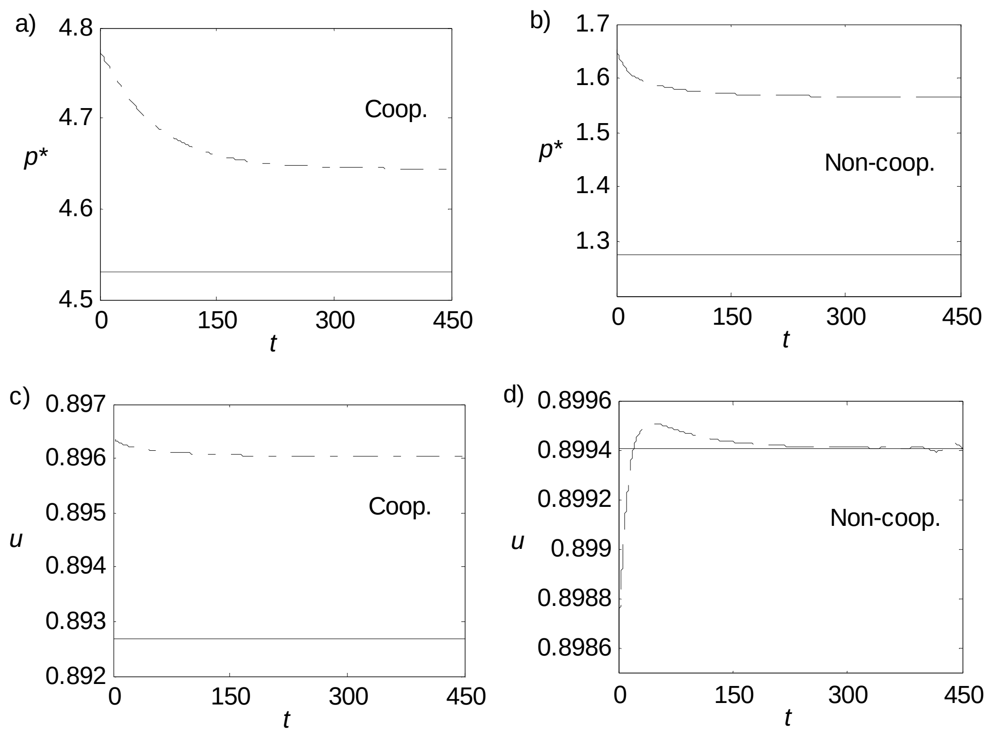
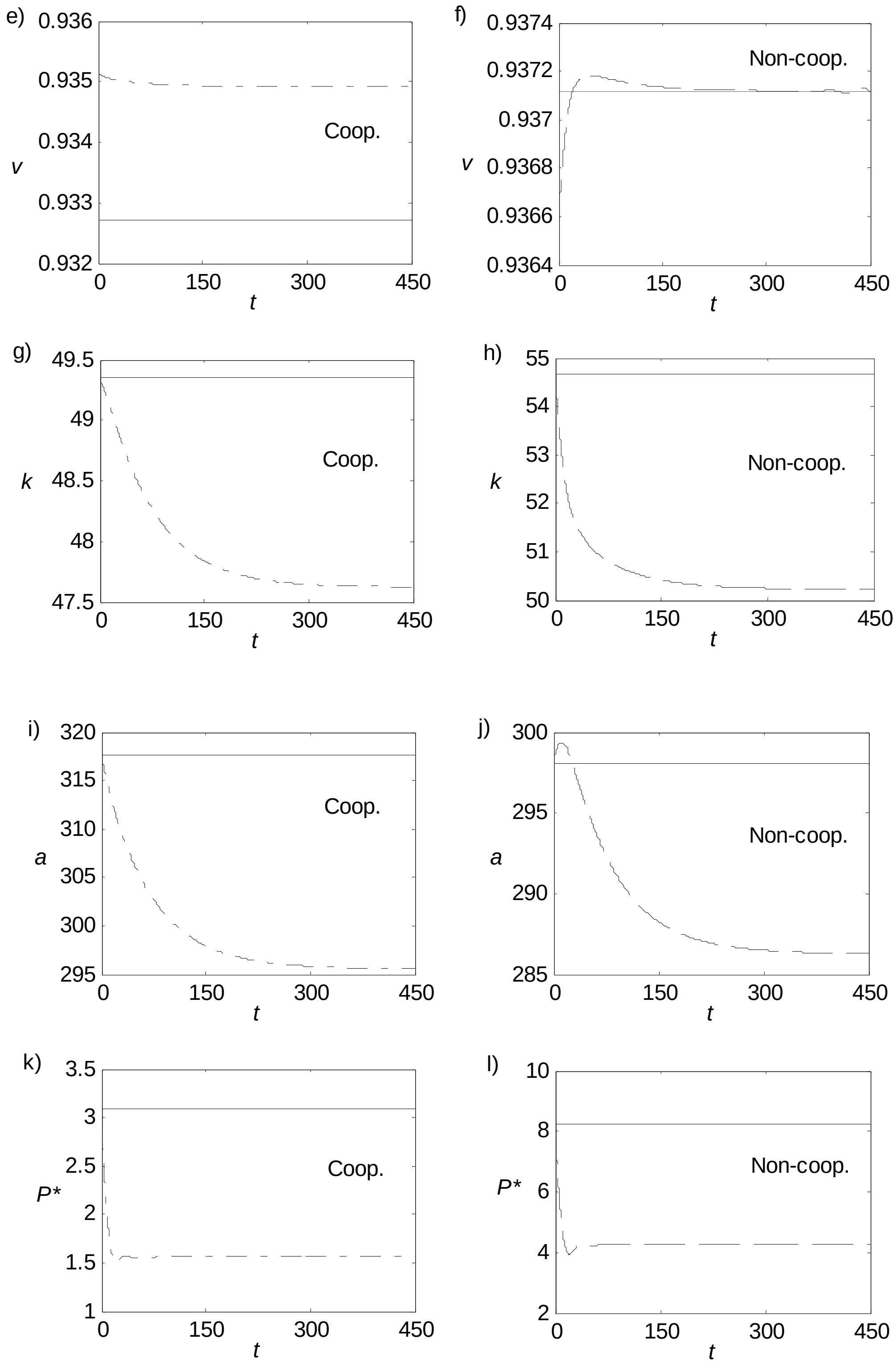


Figure 4. Transitional Dynamics in response to increased resource damage rate:





e)
0.936
0.935
0.934
0.933
0.932
v
Coop.
0
150
300
450
t
f)
0.9374
0.9372
0.937
0.9368
0.9366
0.9364
v
Non-coop.
0
150
300
450
t
g)
49.5
49
48.5
48
47.5
k
Coop.
0
150
300
450
t
h)
55
54
53
52
51
50
k
Non-coop.
0
150
300
450
t
i)
320
315
310
305
300
295
a
Coop.
0
150
300
450
t
j)
300
295
290
285
a
Non-coop.
0
150
300
450
t
k)
3.5
3
2.5
2
1.5
1
P*
Coop.
0
150
300
450
t
l)
10
8
6
4
2
P*
Non-coop.
0
150
300
450
t