Knowledge Spillover, Transboundary Pollution and Growth

Süheyla Özyıldırım

Department of Management, Bilkent University, Bilkent 06533, Ankara

and

Nedim M. Alemdar

Department of Economics, Bilkent University, Bilkent 06533, Ankara

Second draft: June 10, 1999

1 Introduction

Natural resources comprise a significant portion of the world trade, constitute a major source of export revenue to many nations, and in many others, are indispensable as factors of production. Extraction and/or employment of resources as productive inputs may also contribute significantly to environmental damage that may long persist, or that may even be irreversible. Consequently, substantial amounts of economic research has been devoted to study various aspects of natural resource economics (Levhari and Mirman (1980), Dasgupta (1980), Dockner and Long (1993)).

In this study, we focus on the gaming aspects of the trade in natural resources in a complex dynamic setting. We consider the resource trade as a dynamic North/South game (See for instance Galor (1986), Van der Ploeg and De Zeeuw (1992, 1994) etc.). As customary in North/South trade models, we let North specialize in the production of manufactured goods that are consumed in both regions, but accumulated only in the North, and South be the sole supplier of natural resources.

Various studies have extended this basic model to address concerns related to externalities that may accompany trade (Chichilnisky (1994), Copeland and Taylor (1994)). In a previous study, we introduced local pollution in the South due to resource extraction which, however, did not have cumulative effects (Alemdar and Ozyildirim (1998)). Also, to capture beneficial externalities that trade may give rise to, we assumed knowledge accumulated in the North to spillover to South to curb the environmental damage there. The model was then simulated using genetic algorithm to deal with complex dynamics the externalities gave rise to. Our basic finding was that in the presence of substantial knowledge spillovers, and in the absence of tansboundary pollution from the North, noncooperative trade may result in inefficiently small knowledge stock. South's monopoly pricing together with North's inability to internalize knowledge spillovers, though checking the environmental damage in the South, chokes off Northern growth.

In this study, we further extend the North/South trade model to address three specific issues that are important and yet underplayed in our previous work. First, pollution can accumulate over time to inflict lasting damage to the Southern environment; second, as a by-product of Northern production of manufactured goods there may be transboundary pollution in the South; third, there may be more than one producer in the South, adding an extra source of externality by way of a strategic rivalry between them. Northern investment policies become inefficient not only because they ignore the beneficial spillover effects on the Southern pollution, but as they also neglect the transboundary pollution in the South because of the production of manufactured goods. Southern terms of trade, on the other hand, reflects not only the increased pollution costs, but the extent of market power as well. Note that these externalities have opposing effects on the Southern environment and can not easily be disentangled by analytical tools. One aim of our paper is develop a general purpose genetic game algorithm to tackle these complex dynamic problems numerically.

We briefly note few general results here. First, if resources are supplied monopolistically by the South, higher resource pricing leads to inefficiently low resource/knowledge mix. This is especially pronounced initially when the knowledge stock is so low that a rapid accumulation is relatively more desired. Obviously, the resulting pollution levels are less than optimal. The strategic rivalry between two resource producers in the South, on the other hand, deteriorates the terms of trade substantially resulting in inefficiently high resource/knowledge mix in the North, and consequently, overpollution in the South.

The introduction of transboundary pollution introduces a new strategic element and changes the manner the various sources of inefficiencies interact. While the North's inability to internalize the knowledge spillovers leads to 'underinvestment', its indifference to the harmful consequences of its manufacturing activities results in 'overinvestment'. If the extent of transboundary pollution relative to knowledge spillovers is low, then spillover effects are accentuated and underinvestment becomes severe. If, on the other hand, the extent of spillovers is sufficiently high, then noncooperative policies lead to overinvestment.

A slower decay of pollution in the South is reflected by an increase in the Southern terms of trade, thereby implying a reduction in the optimal resource/knowledge mix in the North. Consequently, the Southern terms of trade rises sufficiently to justify a fall in the resource use greater than the knowledge stock to bring forth the desired reduction.

Knowledge stock contributes to the Southern pollution when employed to produce manufactured goods. The extent of the damage, however, is mitigated since the knowledge spills over freely to the South to check the pollution there. We note that there are substantial welfare gains to 'both' parties if the Northern productive activities are less pollutive and that knowledge spillovers are more effective.

2 The Model

2.1 Non-Cooperative North/South Trade

The global economy is composed of two regions, North and South. North employs a concave production technology, $Y = F(K, R, u)$, to produce manufactured goods to consume and invest in the North, or to export to the South at a world price of unity. *Broad capital*, K, measures the current state of the technical knowledge in the North (Griliches, 1979), $R = \sum_{i=1}^{m} R_i$ is the raw material imported from the Southern producers, $i = 1, \ldots, m$, and u stands for all other determinants of output.

The stock of knowledge accumulates in pace with investment,

$$\dot{K}_t = Y_t - p_t R_t - \delta K_t - C_t^n \tag{1}$$

where p_t is the relative market price of resources (Southern terms of trade), $0 < \delta < 1$ is the rate of depreciation of the broad capital[1]. Henceforth, a dot over a variable denotes its time derivative while superscripts n and s stand for North and South, respectively. Equation (1) indicates that the rate of knowledge accumulation is affected not only by the North's desired consumption profile, but also by the South's. No investment takes place in the South so that the proceeds from the resource sale are totally consumed. Nonetheless, South indirectly affects the pace of knowledge accumulation in the North via the resultant terms of trade.

Northern optimal consumption plan maximizes the discounted Northern lifelong welfare, namely,

$$\max_{C_t^n, R_t} J^n = \int_0^\infty e^{-\rho_n t} U(C_t^n) dt \qquad 0 < \rho_n < 1$$

subject to Equation (1) and $K(0) = K_0$ given, $C_t^n \geq 0$ for all t. $U(C_t^n)$ is a strictly concave instantaneous utility function, and ρ_n denotes the Northern time preference rate.

We let the primary resource be produced only in the South by a common constant returns to scale production function which is assumed, for simplicity,

[1]Griliches (1979) discusses extensively various interpretation of depreciation in the context of broad capital.

to be a fixed coefficient type. That is, $R_{it} = bL_{it},\ b > 0$ where L_{it} is the labor employed at time t.[2]

We assume pollution to be localized and internalized only in the South. While resource extraction causes environmental harm locally, North causes some transboundary pollution because of pollutive manufactured goods[3]. However, knowledge 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 inefficient due to the presence of local and transboundary externalities.

The accumulation of pollution $\mathcal{P}_i$ is described by the following equation:

$$\dot{\mathcal{P}}_{it} = \frac{1}{\gamma}\frac{R_{it}^{\gamma}}{K_t^{\phi}} + \psi Y_t - \Psi \mathcal{P}_{it} \tag{2}$$

where $\gamma > 1$, $0 < \phi,\ \psi,\ \Psi < 1$ are common parameters. γ measures the exponential order of environmental damage due to extraction, ϕ is a knowledge diffusion (spillover) parameter, signifying the degree of applicability of knowledge to pollution reduction, ψ parameterizes the extent of transboundary pollution, and Ψ indicates the constant instantaneous rate the pollution decays naturally.

$\mathcal{P}_i$ enters into the Southerners' utility as a stock with a negative marginal utility. Given the Northern demand for resources, Southern producers choose their respective production levels to maximize lifetime utilities, i.e.,

$$\max_{R_{it}} J_i^s = \int_0^{\infty} e^{-\rho_s t} U(C_{it}^s, \mathcal{P}_{it})dt \qquad 0 < \rho_s < 1$$

subject to equations (1), (2) and

$$\begin{aligned} C_{it}^s &= p_t R_{it} \\ p_t &= F_R(K_t, \sum_{i=1}^{m} R_{it}, u) \\ K(0) &= K_0 \quad \text{given}, \quad C_{it}^s \geq 0 \quad \text{for all t}, \end{aligned}$$

[2]If it is assumed that the supply of labor in the South is perfectly elastic at a fixed real wage w_i in terms of the manufacturing goods, the nature of the labor force coupled with the CRS production function would then determine labor income per unit of raw material as w_i/b. Competitive firms in the South will charge a price equal to the private marginal cost of resource extraction w_i/b. The assumed social planners in the South levy export taxes to internalize the social cost of pollution.

[3]For instance, the waste material from production could be dumped in the South (Sachs, Loske, Linz *at al* (1998).

where ρ_s is the common Southern rate of time preference. Instantaneous utility is assumed separable in consumption C_{it}^s, and pollution $\mathcal{P}_{it}$ so that $U(C_{it}^s, \mathcal{P}_{it}) = U(C_{it}^s) - D(\mathcal{P}_{it})$. $U(C_{it}^s)$ is strictly concave and $D(\mathcal{P}_{it})$ is strictly increasing in R_{it} and decreasing in K_t.

2.2 Cooperative North/South Trade

To design cooperative strategies, the parties has to agree in advance upon how to distribute the potential gains from cooperation. The distributive outcome depends on the weights, ω, that are put on the respective fitnesses. 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, we consider an egalitarian allocation and assume exogenously given equal weights.

Let $\rho = \omega_0 \rho_n + \sum_{i=1}^m \omega_i \rho_s$ be the weighted time preference where $\sum_{i=0}^m \omega_i = 1$. The Pareto-efficient solution is found by

$$\max_{C_t^n, R_{1t}, \ldots, R_{mt}} J = \int_0^\infty e^{-\rho t} \{\omega_0 U(C_t^n) + \sum_{i=1}^m \omega_i [U(C_{it}^s) - D(\mathcal{P}_{it})]\} dt$$

subject to

$$\begin{aligned}
\dot{K}_t &= Y_t - p_t R_t - \delta K_t - C_t^n \\
\dot{\mathcal{P}}_{it} &= \frac{1}{\gamma} \frac{R_{it}^\gamma}{K_t^\phi} + \psi Y_t - \Psi \mathcal{P}_{it} \\
C_{it}^s &= p_t R_{it}, \; K(0), \; \mathcal{P}(i0) \; \text{ given, and } C_t^n, C_{it}^s \geq 0, \; i = 1, \ldots, m.
\end{aligned}$$

North/South cooperation has to be supported by binding agreements. Precommitment is difficult in the absence of suitable institutions that can enforce global decisions. Still, cooperative solutions, though lacking credibility, are important in so far as they establish an efficiency benchmark against which other solutions can be compared.

3 Solution Methods

3.1 Genetic Algorithm For Noncooperative Open-Loop Dynamic Games

To determine the open-loop Nash equilibria of an N-person differential game, N optimal control problems need to be solved simultaneously (Başar and

Oldser, 1982). Since GA is a highly parallel mathematical algorithm, we implement N parallel GAs to optimize the control system. We utilize both the optimization and the learning property of the GA to solve the problems of multiple criteria optimization. Our solution procedure uses GAs to visualize situations or problems in which there are more than one performance measure and more than one intelligent controller (player) operating with or without coordination with others.

In this setting, there are N artificially intelligent players (controllers) who update their strategies through GA and a referee, or a fictive player, who administers the parallel implementation of the algorithm and acts as an intermediary for the exchange of best responses. This fictive player (*shared memory*) has no decisive role but provides the best strategies in each iteration to the requested parties *synchronously*. In making decisions, each player has certain expectations as to what the other players will do. These expectations are shaped through the information received from the shared memory in each iteration.

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

```
procedure North GA;                procedure South GA_i;
begin                              begin
  initialize PN(0)                   initialize PS_i(0);
  randomly initialize                randomly initialize
  shared memory;                     shared memory;
  synchronize;                       synchronize;
  evaluate PN(0);                    evaluate PS_i(i0);
  t = 1;                             t = 1;
  repeat                             repeat
    select PN(t) from PN(t-1);         select PS_i(t) from PS_i(t-1);
    copy best to shared memory;        copy best to shared memory;
    synchronize;                       synchronize;
    crossover and mutate PN(t);        crossover and mutate PS_i(t);
    evaluate PN(t);                    evaluate PS_i(t);
    t=t+1;                             t=t+1;
  until(termination condition);      until(termination condition);
end;                               end;
```

In each step of this algorithm, N GAs are solved. In order to reduce the time complexity, the N GAs are solved for one generation while continuously sharing the best 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 extremum.

3.1.1 Genetic Algorithm For Cooperative Games

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

In general, controls may involve constraints so that, either penalty functions or substitution may be used to transform the original problem to an unconstrained optimization problem for GA implementation.[4] For z control variables, T periods, and k 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 zTk, (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 zT based on the best fitness value from the current generations as the optimal solution set.

4 Numerical Experiments

For numerical experimentation, we discretize our model along the lines suggested by Mercenier and Michel (1994) which ensures the steady state invariance between the continuous model and its discrete analog. The discrete-time approximation of *infinite horizon* North/South trade model with steady state

[4] We have both linear equality and inequality constraints. The equalities are eliminated at the start by substitution. The constrained problem is then transformed to an unconstrained problem by associating penalties with all constraint violations which are included in the fitness functions. We used arbitrarily large negative numbers to penalize constraint violations. See Michalewicz (1992) for various GA approaches to handle linear constraints.

invariance is as follows:[5]
North:

$$\max J^n = \sum_{h=0}^{H-1} \theta_h^n \Delta_h U^n(t_h) + \theta_{H-1}^n G^n(K(t_H)) \tag{3}$$

subject to

$$\begin{aligned} K(t_{h+1}) - K(t_h) &= \Delta_h[Y(t_h) - p(t_h)R(t_h) - C^n(t_h) - \delta K(t_h)] \\ K(t_0) \text{ given,} \end{aligned}$$

South:

$$\max J_i^s = \sum_{h=0}^{H-1} \theta_h^s \Delta_h U_i^s(t_h) + \theta_{H-1}^s G_i^s(K(t_H)) \tag{4}$$

subject to

$$\begin{aligned} K(t_{h+1}) - K(t_h) &= \Delta_h[Y(t_h) - p(t_h)R(t_h) - C^n(t_h) - \delta K(t_h)] \\ \mathcal{P}_i(t_{h+1}) - \mathcal{P}_i(t_h) &= \Delta_h[\frac{R_i(t_h)^\gamma}{\gamma K(t_h)^\phi} + \psi Y(t_h) - \Psi \mathcal{P}_i(t_h)] \\ C_i(t_0^s) &= p(t_h)R_i(t_h), \quad K(t_0),\ \mathcal{P}_i(t_0) \quad \text{given,} \end{aligned}$$

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 θ_h^j is the sequence of discount factors of the region $j = n, s$ 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:

$$\theta_h^n = \frac{\theta_{h-1}^n}{1 + \rho_n \Delta_h}, \quad \theta_0^n > 0 \quad \text{and} \quad \theta_h^s = \frac{\theta_{h-1}^s}{1 + \rho_s \Delta_h}, \quad \theta_0^s > 0$$

The functions $G^j(.)$ denote the terminal values.

For numerical experiments, we adopt the following particular functional forms:

$$U(C_t^j) = \begin{cases} \dfrac{{C_t^j}^{1-\sigma}}{1-\sigma} & \text{for } \sigma > 0, \quad \sigma \neq 1 \\ \log\ C_t^j & \text{for } \sigma = 1 \end{cases}$$

[5]See Alemdar and Ozyildirim (1998) for derivation.

and

$$D(\mathcal{P}_{it}) = d\mathcal{P}_{it} \quad d > 0$$

where d converts pollution to utility. Also,

$$Y_t = aK_t^{\alpha} R_t^{\beta}, \quad \alpha + \beta < 1 \text{ and } a > 0.$$

All uncounted inputs u, are normalized to one for simplicity. For the benchmark, the following set of parameter values are assumed:

$\alpha = 0.80$	$\beta = 0.15$	$\gamma = 2$	$a = 1$	$d = 1e-07$
$\sigma = 1.50$	$\delta = 0.08$	$\rho_n = 0.02$	$\rho_s = 0.02$	$\omega_0 = 0.50$
$b = 1.00$	$\psi = 0.01$	$\Psi = 0.05$	$\Delta = 12$	$\phi = 0.25$

These parameter values are assumed for the purposes of illustration, however they are not totally unjustified. Similar values of α, σ, δ, ρ_i and a are used by Auerbach and Kotlikoff (1987) in a different context. The value of d is so chosen to conform with the assumed utility function. The importance of the effetcs of knowledge spillovers is parametrized by ϕ. The genetic operators in this paper were done using the public domain *GENESIS* package (Grefenstette, 1990) on a *SUN SPAC-1000* running *Solaris 2.4* A typical run uses *population size,* j= 50, runs 15 million generations for noncooperative game and 30 million generations for cooperative game, *crossover rate* is 0.60 and *mutation rate* is 0.001. 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 three separate *GAs* for the monopoly and four *GAs* for the duopoly cases. Hence, we are limited by the increased computational costs in our scope for a complete sensitivity analysis.

The selection strategy is *elitist* so that the best performing strategy in the population of survivors is retained. This selection rule is a natural candidate in noncooperative Nash games. Therefore, it is especially crucial for the dynamic noncooperative game algorithm as it requires best responses be mutually exchanged. Were it not for the elitist selection, the best structures may disappear making for a nonconvergence.

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 15 periods (M=15) with a dense *equally* spaced gridding of the time horizon T ($t(M)$ =160), which is sufficient to capture the convergence over time.

5 Results

In the model three important effects, the extent of knowledge spillover from the North, the amount of waste by-product dumped to the South, and the permanence of pollution in the South are parametrized by,ϕ, ψ, Ψ, respectively, and are operative simultaneously. Thus, in order to discern the relative sensitivity of the equilibrium paths to the stregths of these effects, we experiment with the model under different values for, ϕ, ψ, Ψ. Further, equilibrium paths are also sensitive to the market structure in the South. We run the benchmark experiment with monopoly and duopoly market structures.Tables 1 through 7 summarize our numerical findings.

First, we note that because of the North's indifference to the beneficial spillover effects of the knowledge accumulation on the Southern pollution, Northern investment will tend to be too low, while at the same time, to the extent Northern production creates transboundary pollution in the South, the Northern investment will be too high relative to the globally efficient paths. Also, as we note from equation 1, the market power of the South, as reflected in the relative resource price, will affect both the long-run desired knowledge stock and the speed with which investments will take place in the North. Ultimately, the magnitude of deviation from the efficient paths depends significantly on the relative magnitudes of ϕ, ψ, and the degree of monopoly power. In the absence of any waste material from the North, negligence of spillover effects by the North together with the Southern monopoly power lead to diminished growth in the North. Along the cooperative path, as the amount of waste material per output increases, the long-run optimal output fall. This necessitates a decrease in both the knowledge stock and the demand for resources as neither input is inferior. However, since the marginal contribution of knowledge stock to output is larger than the marginal contribution of reasources, the fall in the desired long-run knowledge stock is larger than the resource use implying higher R/K ratios. Resource prices start off higher to reflect now increased costs, but then taper off to facilitate higher R/K ratios.

Noncooperative paths exhibit a similar pattern, and yet adjustments are insufficient and inefficient. First, since the North does not internalize the higher waste from its production process, the output does not fall as much as it does along the cooperative path. Second, since the fact that at the margin one unit of the knowledge stock contributes relatively more to the creation of waste is discounted by the North, and also the fact that the South uses its monopoly power to reflect the now higher pollution costs, all lead to lower R/K ratios.

We start our discussion of how the spillover effects operate in the presence of tranboundary pollution again with the cooperative mode. With higher knowledge spillovers, for given levels of knowledge stock, pollution and resource, the level of ouput is higher. Moreover, since resources contribute relatively less with higher spilover rates, R/K ratios rise. As the pollution costs are relatively less with higher spillover rates, resouce prices fall.

As for the noncooperative paths, again the long-run desired output rises, but much more so than the cooperative case since the North is indifferent to the harmful consequences of the waste on the Southern environment. In this instance, the rate of spillover is so high that its distorting effects are overwhelmed by the distortions created by the presence of transboundary pollution. Since the South internalizes the local costs of pollution, higher spillover first partially offsets the monopoly power to encourage faster build up of knowledge stock. Given initially lower resource prices and lack of care for the Southern environment, North overinvests in knowledge accumulation. As the benefit from incremental investment falls in the form of reduced pollution costs to the South, the South starts exercising its monopoly power.

The discussion of how the equilibrium paths are influenced by the stubborness of pollution in the South is similar to the effects of an increase in the waste/output ratio. Along the efficient paths, as the pollution becomes more persistent, lower levels of ouput can be sustained which necessitate a reduction in both resource use and knowledge stock. As the stock of knowledge adds more the pollution stock at the margin which now lingers around longer, the fall in knowledge stock is greater than the fall in resource use to bring about a rise in the R/K ratio. The noncooperative paths show similar, but inefficient adjustments which are ultimately indicated by lower R/K ratios and higher prices relative to the efficient paths.

Finally, Nash-Cournot duopoly in resource production in the South results in overproduction of resources and overpollution. The main culprit, this time is the 'policy externality' between the Southern producers in. The overpollution results not only from the rivalry in resource production, but also from the fact that neither producer internalizes the 'local' pollution due to resource extraction in the other producer country. Consequently, the resulting market prices are inefficiently low.

6 Conclusion

In this study, we extended the North/South trade model to address three specific issues. First, pollution can inflict lasting damage to the Southern environment; second, there may be transboundary pollution from the North; third, there may be more than one producer in the South. We develop a general purpose genetic game algorithm to tackle these complex dynamics numerically.

If resources are supplied monopolistically by the South, higher resource pricing leads to inefficiently low resource/knowledge mix. This is especially pronounced initially when the knowledge stock is so low that a rapid accumulation is relatively more desired. Obviously, the resulting pollution levels are less than optimal. The strategic rivalry between two resource producers in the South, on the other hand, deteriorates the terms of trade substantially resulting in inefficiently high resource/knowledge mix in the North, and consequently, overpollution in the South.

The introduction of transboundary pollution introduces a new strategic element and changes the manner the various sources of inefficiencies interact. While the North's inability to internalize the knowledge spillovers leads to 'underinvestment', its indifference to the harmful consequences of its manufacturing activities results in 'overinvestment'. If the extent of transboundary pollution relative to knowledge spillovers is low, then spillover effects are accentuated and underinvestment becomes severe. If, on the other hand, the extent of spillovers is sufficiently high, then noncooperative policies lead to overinvestment.

A slower decay of pollution in the South is reflected by an increase in the Southern terms of trade, thereby implying a reduction in the optimal resource/knowledge mix in the North. Consequently, the Southern terms of trade rises sufficiently to justify a fall in the resource use greater than the knowledge stock to bring forth the desired reduction.

Knowledge stock contributes to the Southern pollution when employed to produce manufactured goods. The extent of the damage, however, is mitigated since the knowledge spills over freely to the South to check the pollution there. We note that there are substantial welfare gains to 'both' parties if the Northern productive activities are less pollutive and that knowledge spillovers are more effective.

Table 1: $\phi = 0.25, \psi = 0.00, \Psi = 0.05$

Non-Cooperative

time	K_t	p_t	R_t	R_t/K_t	Y_t	$\mathcal{P}_t$	C_t^n	C_t^s
0	500000.0	78.0	147.4	0.000295	76636.6	4900.1	17891.2	11495.5
1	586999.0	89.6	145.6	0.000248	86975.0	6556.8	19963.2	13046.2
2	671065.5	100.6	144.1	0.000215	96656.0	6978.0	21874.2	14498.4
3	750244.4	110.7	143.0	0.000191	105553.4	6961.4	23591.4	15833.0
4	823558.2	119.9	142.1	0.000173	113616.1	6805.7	25068.3	17042.4
5	891006.8	128.4	141.2	0.000158	120883.0	6614.1	26501.0	18132.5
6	950635.4	135.8	140.6	0.000148	127229.9	6441.9	27695.8	19084.5
7	1003421.3	142.4	139.9	0.000139	132752.1	6285.1	28736.9	19912.8
8	1049364.6	148.1	139.3	0.000133	137506.3	6150.4	29591.4	20625.9
9	1089442.8	152.9	138.9	0.000128	141637.8	6044.4	30385.6	21245.7
10	1123655.9	157.0	138.6	0.000123	145140.2	5959.7	31032.9	21771.0
11	1152981.4	160.6	138.4	0.000120	148122.2	5890.3	31547.4	22218.3
12	1178396.9	163.9	137.8	0.000117	150639.6	5816.1	32061.3	22595.9
13	1198924.7	166.3	137.8	0.000115	152724.7	5768.3	32435.8	22908.7
14	1216520.0	172.0	134.2	0.000110	153912.2	5562.5	32689.2	23086.8
15	1226295.2	157.8	149.7	0.000122	157456.1	6265.6	35734.1	23618.4
16	1226295.2	163.1	144.0	0.000117	156544.3	6265.6	34959.0	23481.6

Cooperative

time	K_t	p_t	R_t	R_t/K_t	Y_t	$\mathcal{P}_t$	C_t^n	C_t^s
0	500000.0	55.7	298.8	0.000598	81324.9	20148.8	12781.5	16650.2
1	642717.5	67.2	297.4	0.000463	99666.7	26797.1	15572.2	19969.4
2	795210.2	79.3	295.0	0.000371	118252.0	28205.9	18362.4	23402.2
3	949657.9	90.0	294.7	0.000310	136665.4	27977.2	21125.7	26533.6
4	1106060.6	100.7	294.0	0.000266	154655.7	27181.6	23848.7	29614.4
5	1258553.3	111.0	293.1	0.000233	171681.2	26262.7	26406.7	32534.2
6	1403225.8	120.1	292.8	0.000209	187571.0	25452.2	28745.0	35163.6
7	1540078.2	128.7	292.2	0.000190	202242.4	24725.8	30988.1	37621.2
8	1665200.4	135.8	292.4	0.000176	215635.9	24168.3	32946.8	39697.9
9	1782502.4	142.8	291.8	0.000164	227862.3	23648.1	34792.6	41671.9
10	1888074.3	149.3	290.8	0.000154	238674.1	23143.6	36406.8	43401.2
11	1981915.9	154.0	291.5	0.000147	248462.1	22845.1	37862.0	44878.4
12	2067937.4	159.4	289.4	0.000140	257023.4	22393.4	39102.0	46132.6
13	2144183.8	162.3	291.6	0.000136	265078.8	22293.7	40340.6	47338.4
14	2214565.0	168.8	290.3	0.000131	271387.1	22027.1	41314.6	48997.3
15	2261485.8	188.7	260.1	0.000115	271393.6	19279.5	41388.1	49086.7
16	2261485.8	183.0	274.3	0.000121	272871.4	19279.5	41750.6	50201.8

Table 2: $\phi = 0.25, \psi = 0.01, \Psi = 0.05$

Non-Cooperative

time	K_t	p_t	R_t	R_t/K_t	Y_t	$\mathcal{P}_t$	C_t^n	C_t^s
0	500000.0	84.4	134.4	0.000269	75581.0	13142.5	17401.2	11337.1
1	582111.4	97.3	131.1	0.000225	85047.0	19197.6	19269.4	12757.0
2	659530.8	109.6	128.2	0.000194	93661.7	22377.8	20936.0	14049.3
3	730498.5	121.3	125.2	0.000171	101284.5	24323.0	22324.5	15192.7
4	794428.2	132.0	122.7	0.000154	107987.4	25713.6	23591.8	16198.1
5	850146.6	141.9	120.2	0.000141	113648.4	26776.6	24630.5	17047.3
6	897654.0	149.7	118.7	0.000132	118483.2	27675.3	25477.1	17772.5
7	938709.7	157.3	116.8	0.000124	122498.2	28398.6	26143.0	18374.7
8	973313.8	163.1	115.8	0.000119	125943.8	29035.7	26890.0	18891.6
9	1000879.8	168.4	114.5	0.000114	128573.4	29532.0	27310.9	19286.0
10	1023753.7	173.3	113.1	0.000110	130670.4	29906.2	27801.0	19600.6
11	1040176.0	174.5	113.9	0.000110	132484.5	30298.0	27931.4	19872.7
12	1057771.3	180.3	111.3	0.000105	133809.6	30494.0	28236.7	20071.4
13	1068328.4	180.9	111.9	0.000105	134988.8	30733.8	28492.2	20248.3
14	1077712.6	179.6	113.8	0.000106	136276.6	31058.1	28787.2	20441.5
15	1087683.3	175.8	117.8	0.000108	137992.3	31559.1	30278.8	20698.9
16	1087683.3	177.3	116.6	0.000107	137782.1	31682.3	30100.2	20667.3

Cooperative

time	K_t	p_t	R_t	R_t/K_t	Y_t	$\mathcal{P}_t$	C_t^n	C_t^s
0	500000.0	63.8	278.3	0.000557	84304.9	27592.2	17742.9	17764.4
1	605571.8	75.3	272.7	0.000450	97969.7	38791.3	20554.1	20538.8
2	706744.9	86.2	269.0	0.000381	110630.8	43767.7	23203.7	23189.5
3	799120.2	96.1	265.3	0.000332	121800.7	46247.5	25527.2	25501.3
4	881231.7	105.3	261.6	0.000297	131435.8	47671.1	27536.3	27535.8
5	951612.9	112.7	259.7	0.000273	139619.4	48781.7	29220.3	29260.2
6	1011730.2	119.1	257.9	0.000255	146474.4	49669.7	30675.2	30706.3
7	1061583.6	124.1	256.0	0.000241	152055.6	50365.8	31805.4	31780.0
8	1104105.6	128.8	254.2	0.000230	156737.6	50911.1	32740.6	32736.0
9	1139296.2	130.0	257.9	0.000226	161071.7	51905.1	33480.0	33515.4
10	1174486.8	132.9	256.0	0.000218	164860.8	52491.0	34070.5	34021.0
11	1208211.1	135.0	257.9	0.000213	168820.1	53288.9	34777.6	34819.6
12	1239002.9	140.5	252.3	0.000204	171689.9	53365.8	35417.5	35441.5
13	1259530.8	140.9	254.2	0.000202	174153.3	53813.7	35756.7	35801.2
14	1281524.9	166.5	222.6	0.000174	173103.1	51132.6	37055.6	37068.9
15	1239002.9	152.5	230.0	0.000186	169324.5	50286.3	35119.6	35084.7
16	1239002.9	150.2	235.6	0.000190	169933.5	50286.3	35428.6	35384.7

Table 3: $\phi = 0.25, \psi = 0.015, \Psi = 0.05$

Non-Cooperative

time	K_t	p_t	R_t	R_t/K_t	Y_t	$\mathcal{P}_t$	C_t^n	C_t^s
0	500000.0	87.2	129.3	0.000259	75151.2	17301.8	17207.0	11272.7
1	580058.7	101.3	124.6	0.000215	84155.1	25441.4	18911.8	12623.3
2	654643.2	114.6	120.8	0.000184	92279.0	29863.9	20477.5	13841.8
3	721700.9	127.3	117.0	0.000162	99295.2	32637.9	21761.0	14894.3
4	780547.4	138.5	114.0	0.000146	105310.2	34635.6	22907.3	15796.5
5	830498.5	148.9	111.1	0.000134	110234.4	36148.9	23781.1	16535.2
6	872238.5	157.3	109.0	0.000125	114322.4	37370.9	24486.9	17148.4
7	907135.9	164.9	107.0	0.000118	117635.6	38348.2	25081.5	17645.3
8	935190.6	171.0	105.5	0.000113	120283.2	39137.6	25543.8	18042.5
9	957771.3	175.6	104.6	0.000109	122443.0	39792.9	25972.3	18366.5
10	975562.1	182.3	101.8	0.000104	123763.6	40174.7	26013.7	18564.5
11	989247.3	186.4	100.5	0.000102	124905.1	40475.1	26402.3	18735.8
12	996774.2	186.5	101.2	0.000101	125785.4	40774.7	26434.4	18867.8
13	1005669.6	184.0	103.6	0.000103	127139.6	41229.3	26702.7	19070.9
14	1016617.8	188.9	101.6	0.000100	127858.5	41454.9	27008.2	19178.8
15	1020723.4	188.6	102.1	0.000100	128372.6	41656.3	27458.8	19255.9
16	1020723.4	186.9	103.2	0.000101	128585.1	41656.3	27639.4	19287.8

Cooperative

time	K_t	p_t	R_t	R_t/K_t	Y_t	$\mathcal{P}_t$	C_t^n	C_t^s
0	500000.0	67.8	268.3	0.000537	78556.5	30386.0	12950.8	18192.8
1	588954.1	78.9	262.6	0.000446	89217.1	43144.6	14693.3	20727.7
2	669110.5	89.0	258.0	0.000386	98500.5	48948.5	16235.8	22952.2
3	738514.2	97.9	254.0	0.000344	106282.1	51910.6	17535.1	24859.7
4	796187.7	105.3	250.7	0.000315	112613.2	53662.2	18601.5	26406.6
5	843108.5	111.3	248.4	0.000295	117702.9	54867.7	19441.5	27635.8
6	881231.7	116.1	246.6	0.000280	121788.9	55780.4	20134.1	28631.0
7	911534.7	120.0	245.2	0.000269	124995.6	56482.5	20700.8	29417.0
8	934995.1	123.0	244.0	0.000261	127469.6	57024.0	21121.0	30001.3
9	953567.9	125.4	242.9	0.000255	129406.5	57432.4	21443.6	30455.5
10	968230.7	125.9	244.6	0.000253	131175.8	58026.0	21695.2	30800.2
11	982893.5	129.3	241.3	0.000245	132430.9	58138.8	21878.1	31188.1
12	991691.1	129.6	241.2	0.000243	133478.6	58338.8	22063.6	31265.1
13	1001466.3	130.9	241.0	0.000241	134479.6	58554.1	22239.0	31553.0
14	1008308.9	131.7	242.3	0.000240	135209.1	58878.0	22387.8	31912.2
15	1011241.4	134.8	235.5	0.000233	135013.5	58345.7	22359.6	31754.6
16	1011241.4	133.4	239.8	0.000237	135277.8	58345.7	22400.1	31978.4

Table 4: $\phi = 0.50, \psi = 0.01, \Psi = 0.05$

Non-Cooperative

time	K_t	p_t	R_t	R_t/K_t	Y_t	$\mathcal{P}_t$	C_t^n	C_t^s
0	500000.0	22.6	631.6	0.000857	95333.9	14825.5	24000.6	14300.1
1	704398.8	31.0	603.6	0.000597	124557.0	23481.7	30134.1	18683.6
2	937047.9	41.5	559.1	0.000425	154713.8	29895.7	35909.2	23207.1
3	1184653.0	54.7	503.8	0.000311	183743.6	35406.7	41330.0	27561.5
4	1425610.9	70.7	443.7	0.000234	209057.1	40238.9	45785.5	31358.6
5	1639980.5	89.4	383.9	0.000183	228822.7	44244.7	49175.7	34323.4
6	1809481.9	109.6	331.4	0.000152	242157.4	47246.6	51520.0	36323.6
7	1924144.7	127.9	292.7	0.000137	249661.8	49228.6	52603.2	37449.3
8	1992277.6	139.3	273.7	0.000128	254133.5	50505.8	53723.2	38120.0
9	2027175.0	147.3	260.4	0.000123	255772.6	51180.7	53986.4	38365.9
10	2042131.0	152.8	251.3	0.000125	255914.4	51447.2	53464.4	38387.2
11	2050439.9	150.8	256.2	0.000127	257486.3	51752.2	54135.8	38622.9
12	2058748.8	148.5	261.7	0.000121	259152.9	52085.6	55303.1	38872.9
13	2062072.3	155.0	249.3	0.000128	257602.1	52006.2	54134.5	38640.3
14	2060410.6	147.6	263.8	0.000122	259635.4	52249.7	54057.0	38945.3
15	2082013.7	154.1	253.3	0.000125	260220.4	52393.2	54626.3	39033.1
16	2082013.7	150.8	259.9	0.000129	261216.3	52393.2	55472.8	39182.4

Cooperative

time	K_t	p_t	R_t	R_t/K_t	Y_t	$\mathcal{P}_t$	C_t^n	C_t^s
0	500000.0	20.7	1211.3	0.002423	105115.2	25064.6	25164.1	25125.5
1	677908.1	27.1	1196.7	0.001765	133854.7	36524.2	32494.4	32464.9
2	853861.2	33.7	1171.8	0.001372	160485.7	42783.4	39480.2	39500.1
3	1012219.0	39.8	1148.3	0.001134	183328.3	46976.8	45724.3	45710.9
4	1143206.3	45.2	1124.9	0.000984	201449.3	50065.4	50891.6	50873.8
5	1241935.5	49.4	1107.3	0.000892	214743.0	52396.7	54673.8	54686.3
6	1314271.8	52.6	1092.6	0.000831	224243.6	54116.3	57495.4	57452.1
7	1364125.1	55.0	1080.9	0.000792	230649.6	55326.7	59380.5	59450.9
8	1396383.2	56.4	1076.5	0.000771	234859.2	56198.2	60770.3	60667.6
9	1416911.0	57.9	1064.8	0.000751	237227.3	56661.6	61567.0	61655.7
10	1424731.2	58.9	1054.5	0.000740	237928.5	56806.1	62112.0	62082.3
11	1421798.6	59.6	1041.4	0.000732	237088.6	56629.9	62291.5	62112.2
12	1409090.9	60.3	1020.8	0.000724	234690.4	56082.3	61604.9	61580.2
13	1394428.2	61.0	988.6	0.000709	231617.2	55192.9	60246.4	60305.3
14	1388563.1	57.4	1038.4	0.000748	232546.1	55473.4	59635.6	59626.0
15	1414956.0	59.1	1039.9	0.000735	236125.5	55979.0	61508.0	61421.0
16	1414956.0	59.1	1041.4	0.000736	236175.4	56202.6	61471.4	61507.5

Table 5: $\phi = 0.25, \psi = 0.01, \Psi = 0.02$

Non-Cooperative

time	K_t	p_t	R_t	R_t/K_t	Y_t	$\mathcal{P}_t$	C_t^n	C_t^s
0	500000.0	110.7	97.7	0.000195	72048.8	10797.4	16109.5	10807.3
1	561583.6	124.8	94.6	0.000168	78691.5	19611.2	17415.7	11803.7
2	616129.0	135.8	93.5	0.000152	84591.3	26925.8	18580.1	12688.7
3	664516.1	146.8	91.5	0.000138	89586.9	32974.9	19541.8	13438.0
4	705865.1	158.8	88.4	0.000125	93521.9	37899.6	20091.9	14028.3
5	741055.7	170.5	85.1	0.000115	96680.0	41884.8	19667.8	14502.0
6	779765.4	175.2	86.4	0.000111	100941.2	45453.6	22465.7	15141.2
7	791202.3	184.1	82.7	0.000104	101441.6	48091.9	21243.0	15216.2
8	811437.0	185.5	83.9	0.000103	103742.0	50405.5	22092.7	15561.3
9	825513.2	197.7	79.1	0.000096	104256.5	52064.3	21770.5	15638.5
10	835190.6	200.1	78.9	0.000094	105187.2	53425.9	22154.0	15778.1
11	840469.2	190.9	83.8	0.000100	106690.6	54799.1	22643.0	16003.6
12	850146.6	202.9	78.9	0.000093	106695.7	55680.5	22899.5	16004.4
13	847507.3	202.4	78.9	0.000093	106427.4	56318.6	21782.9	15964.1
14	858064.5	187.9	87.1	0.000102	109101.1	57390.3	22477.9	16365.2
15	877419.4	197.9	83.7	0.000095	110392.0	58235.6	23639.7	16558.8
16	877419.4	198.9	83.2	0.000095	110299.9	58235.6	23561.4	16545.0

Cooperative

time	K_t	p_t	R_t	R_t/K_t	Y_t	$\mathcal{P}_t$	C_t^n	C_t^s
0	500000.0	83.1	208.1	0.000416	75790.5	18869.0	12489.4	17289.4
1	572140.8	94.8	202.3	0.000354	84059.4	33353.0	13908.9	19173.9
2	634604.1	104.6	200.3	0.000316	91079.6	44807.8	14893.3	20945.8
3	688269.8	114.3	196.4	0.000285	96773.7	53702.4	15810.2	22456.1
4	729618.8	120.2	194.5	0.000267	101337.9	60736.8	16663.3	23372.6
5	764809.4	126.1	192.5	0.000252	105045.2	66283.6	17321.6	24266.2
6	792082.1	131.9	190.5	0.000241	107699.7	70601.6	17656.7	25136.8
7	810557.2	133.9	190.5	0.000235	109777.2	74090.6	18177.1	25509.2
8	825513.2	139.7	186.6	0.000226	110841.1	76543.4	18206.8	26080.1
9	831671.6	141.7	184.7	0.000222	111346.0	78311.0	18351.1	26167.9
10	835190.6	141.7	184.7	0.000221	111789.3	79700.5	18513.0	26167.9
11	838709.7	145.6	178.8	0.000213	111695.0	80315.6	18488.8	26036.1
12	839589.4	143.6	180.8	0.000215	112072.2	80966.0	18351.1	25967.4
13	846627.6	137.8	188.6	0.000223	113789.8	82223.9	18388.8	25984.6
14	866862.2	135.8	184.7	0.000213	116641.3	83193.8	18688.0	25085.2
15	909090.9	157.3	171.0	0.000188	118859.9	83172.6	19229.7	26903.0
16	909090.9	153.4	178.8	0.000197	119388.7	83172.6	19227.6	27433.8

Table 6: $\phi = 0.25, \psi = 0.01, \Psi = 0.08$

Non-Cooperative

time	K_t	p_t	R_t	R_t/K_t	Y_t	$\mathcal{P}_t$	C_t^n	C_t^s
0	500000.0	71.6	163.1	0.000326	77813.0	15341.3	18255.8	11672.0
1	594623.7	83.9	159.3	0.000268	89068.5	16784.6	20448.6	13360.3
2	686901.3	96.0	155.6	0.000226	99610.8	17669.1	22548.7	14941.6
3	772922.8	107.5	152.3	0.000197	109121.8	18494.7	24402.9	16368.3
4	851124.1	117.9	149.6	0.000176	117549.4	19264.8	26027.1	17632.4
5	920723.4	127.4	147.0	0.000160	124850.5	19936.8	27382.0	18727.6
6	981720.4	135.9	144.7	0.000147	131116.8	20522.3	28545.4	19667.5
7	1034115.3	143.1	143.0	0.000138	136446.9	21043.0	29536.1	20467.0
8	1078690.1	149.4	141.5	0.000131	140899.3	21474.8	30341.2	21134.9
9	1116226.8	154.7	140.2	0.000126	144620.5	21843.6	31022.6	21693.1
10	1147507.3	159.1	139.3	0.000121	147699.1	22152.8	31593.1	22154.9
11	1173313.8	162.9	138.3	0.000118	150194.4	22396.2	32105.7	22529.2
12	1193646.1	166.0	137.5	0.000115	152139.2	22584.0	32392.9	22820.9
13	1210850.4	168.3	137.1	0.000113	153820.7	22760.2	32771.7	23073.1
14	1224144.7	173.8	133.4	0.000109	154542.1	22666.2	33038.2	23181.3
15	1228836.8	154.7	153.5	0.000125	158312.9	24150.9	36259.0	23746.9
16	1228836.8	155.3	152.8	0.000124	158207.2	24150.9	36169.2	23731.1

Cooperative

time	K_t	p_t	R_t	R_t/K_t	Y_t	$\mathcal{P}_t$	C_t^n	C_t^s
0	500000.0	54.7	332.0	0.000664	81587.5	34668.1	13157.4	18166.2
1	623167.2	65.5	327.2	0.000525	97250.8	35914.5	15638.6	21413.4
2	747311.8	77.2	320.3	0.000429	112079.7	35825.7	17962.7	24719.8
3	862658.8	86.9	317.4	0.000368	125621.8	36341.3	20136.8	27593.2
4	969208.2	96.7	312.5	0.000322	137565.4	36637.8	22069.5	30220.6
5	1062072.3	104.5	310.6	0.000292	147895.3	37239.5	23710.4	32457.9
6	1143206.3	112.3	306.7	0.000268	156501.9	37525.2	25060.7	34445.4
7	1209677.4	118.2	304.7	0.000252	163577.5	37927.6	26230.3	36011.3
8	1264418.4	122.1	304.7	0.000241	169559.5	38476.7	27294.4	37201.6
9	1311339.2	127.0	301.8	0.000230	174265.0	38597.7	28026.5	38317.4
10	1347507.3	130.9	299.8	0.000223	177831.7	38714.1	28591.1	39240.5
11	1373900.3	132.8	299.8	0.000218	180635.2	38978.6	29105.0	39826.1
12	1395405.7	134.8	298.8	0.000214	182823.6	39088.7	29526.3	40280.0
13	1412023.5	136.7	297.9	0.000211	184403.3	39135.2	29733.7	40730.2
14	1423753.7	128.9	317.4	0.000223	187784.2	41598.1	30356.0	40921.2
15	1455034.2	157.2	250.0	0.000172	185064.8	34670.5	29347.7	39314.4
16	1455034.2	156.3	252.9	0.000174	185268.3	34670.5	29337.6	39528.0

Table 7: Duopoly in the South

time	K_t	p_t	R_{1t}	R_{2t}	R_t/K_t
0	500000.0	22.6	316.4	316.1	0.001265
1	608504.4	26.8	311.4	311.1	0.001023
2	718475.1	30.9	306.7	308.8	0.000857
3	825513.2	35.0	302.3	303.2	0.000734
4	928152.5	38.8	299.7	299.7	0.000646
5	1023460.4	42.4	296.5	296.8	0.000580
6	1111437.0	45.7	294.1	292.7	0.000528
7	1189149.6	48.2	293.0	293.5	0.000493
8	1260997.1	50.8	290.9	292.7	0.000463
9	1324046.9	53.3	288.6	288.9	0.000436
10	1378299.1	55.1	286.8	289.1	0.000418
11	1429618.8	57.0	285.0	287.7	0.000401
12	1469208.2	58.8	282.1	284.2	0.000385
13	1505865.1	59.5	285.0	286.5	0.000380
14	1541055.7	61.5	283.0	279.2	0.000365
15	1571847.5	59.3	297.7	299.7	0.000380
16	1571847.5	60.5	292.1	292.4	0.000372
time	$\mathcal{P}_{1t}$	$\mathcal{P}_{2t}$	C_t^n	C_{1t}^s	C_{2t}^s
0	34033.9	33992.0	32009.1	7154.9	7148.3
1	47807.5	47751.5	36770.3	8352.3	8344.4
2	53744.1	53982.1	41481.2	9487.0	9550.5
3	56671.7	56873.0	45666.2	10595.8	10626.6
4	58650.4	58730.9	49683.8	11636.3	11636.3
5	60143.1	60208.1	53176.1	12557.1	12569.5
6	61481.4	61348.4	56454.1	13431.6	13364.6
7	62813.0	62822.3	59149.7	14127.2	14155.5
8	63973.4	64161.0	61709.8	14765.1	14854.4
9	64917.4	65022.4	63802.2	15366.9	15382.5
10	65764.0	66042.6	65326.6	15806.0	15935.3
11	66528.6	66902.3	67380.6	16252.6	16403.1
12	66983.7	67333.5	68225.0	16599.9	16720.7
13	67935.0	68218.5	69442.4	16972.0	17059.3
14	68475.8	68224.2	70103.4	17407.3	17172.8
15	70766.0	70873.2	75153.5	17665.7	17787.5
16	71032.5	71104.4	74496.5	17659.8	17677.5

References

Alemdar, N.M. and S. Ozyildirim, 1998, A genetic game of trade, growth and externalities, *Journal of Economic Dynamics and Control*, 22, 811-832.

Auerbach, A.L. and L.J. Kotlikoff, 1987, *Dynamic Fiscal Policy*, Cambridge University Press, Cambridge, New York.

Başar, T., and G.J. Oldser, 1982, *Dynamic Noncooperative Game Theory*, Academic Press, New York.

Chichilnisky, G., 1994, North, South trade and the global environment, *American Economic Review*, 84, 851-874.

Copeland, B.R. and M.S. Taylor, 1994, North-South trade and environment problems, *Quarterly Journal of Economics*, 109, 755-787.

Dasgupta, P., 1982, *The Control of Resources*, Basil Blackwell, Oxford.

Dockner, E.J., and N.V. Long, 1993, International pollution control: cooperative versus noncooperative strategies, *Journal of Environmental Economics and Management*, 24, 13-29.

Galor, O., 1986, Global dynamic inefficiency in the absence of international policy coordination: A North-South case, *Journal of International Economics*, 21, 137-149.

Goldberg, D. E., 1989, *Genetic Algorithms in Search, Optimization and Machine Learning*, Addision Wesley, Reading, Massachusetts.

Grefenstette, J.J., 1986, Optimization of control parameters for genetic algorithm, *IEEE Transactions on Systems, Man and Cybernetics*, 16, 122-128.

Grefenstette, J.J., 1990, A user's guide to GENESIS Version 5.0, *manuscript*

Griliches, Z., 1979, Issues in assessing the contribution of R&D to productivity growth, *The Bell Journal of Economics*, l0, 92-116.

Holland, J.H., 1975, *Adaptation in Natural and Artificial Systems*, Ann Arbor, University of Michigan Press.

Krishnakumar, K. and Goldberg, D. E., 1992, Control system optimization using genetic algorithm, *Journal of Guidance, Control, and Dynamics*, 15, 735-738.

Levhari, D. and L. Mirman, 1980, The great fishwar: an example using a dynamic Cournot-Nash solution, *Bell Journal*, 11, 322-334.

Mercenier, J., and P. Michel, 1994, Discrete-time finite horizon approximation of infinite horizon optimization problems with steady-state invariance, *Econometrica*, 62, 635-656.

Michalewicz, Z., 1992, *Generic Algorithm + Data Structures = Evolution Program*, Springer Verlag, Berlin Heidelberg, New York.

Sachs, W., R. Loske and M. Linz, *et al*, 1998, *Greening the North: A Post-Industrial Blueprint for Ecology and Equity*, Zed Books Ltd., London.
Van Der Ploeg, F., and A.J. De Zeeuw, 1992, International aspects of pollution control, *Environmental and Resource Economics*, 2, 117-139.
Van Der Ploeg, F., and A.J. De Zeeuw, 1994, Investment in Clean technology and Transboundary Pollution Control, in C. Carraro (ed.) *Trade, Innovation, Environment*, Kluwer Academic Publishers.