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**ON ENDOGENOUS GROWTH: THE IMPLICATIONS OF
ENVIRONMENTAL EXTERNALITIES**

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On Endogenous Growth: The Implications of Environmental Externalities

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Abstract

This paper uses an endogenous growth model to examine the interaction between trade, economic growth, and the environment. We find that whether trade enhances or retards growth depends on the relation between factor intensities of exportable, importable, and R&D and the relative abundance of the factor R&D uses more intensively. Depending on the intertemporal elasticity of substitution, the long-run rate of economic growth changes with environmental externalities. Concerns about the environment can explain a significant part of cross-country difference in growth rates. For the empirically reported range of the elasticity of intertemporal substitution, countries which care more about the environment grow faster. The effects of trade on the environment and welfare depend on the elasticities of supply for the two traded goods, the terms of trade effect on growth, and pollution intensities. The decentralized and Pareto optimal growth rates are, in general, different. The market growth rate is bigger than the optimal rate the larger the degree of monopoly power in the innovation sector and the stronger the effects of environmental externalities. The policy implications of this divergence are discussed. We also consider numerical exercises to broaden the insights from the analytical results and allow for incorporating pollution abatement (*Journal of Economic Literature* Classification Numbers: F11, O31, O41, Q20).

Key Words

Endogenous growth, environment, innovation, trade.

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I. Introduction

The new growth theory has succeeded to a large extent in accounting for many of (what Kaldor, 1961, and others call) the "stylized" facts of economic growth.¹ However, it ignores altogether the interaction between growth and environment.² If what motivates the study of growth is its implication on welfare, then there is a strong motivation for studying environmental externalities because they have direct and indirect welfare effects. The direct effects are related to the harm on human health and the damage to the amenity value of the environment. The indirect effects are the reduced productivity impacts of global warming, desertification, deforestation, etc. Substantial evidence has been gathered on these effects (e.g., see the World Bank, 1992). Many of these environmental problems are blamed on the process of economic growth. Needless to emphasize, the omission of environment would have serious implications on the predictions of the new growth theory. Moreover, environmental policies have never been analyzed in this framework.

Parallel to the new growth theory, a large body of literature on modeling the linkages between growth and environment has accumulated. These models suffer from at least two limitations. First, they ignore innovations, the engine of growth, and trade. According to Grossman and Helpman (1994) "a story of growth that neglects technological progress is both ahistorical and implausible" (p. 26). Because they ignore innovations and their positive spillover effects on production, the common result from these models is that optimal preservation of environmental quality and economic growth

¹Contributions to this theory are made by Romer (1986, 1990), Lucas (1988), Grossman and Helpman (1991a), Rebelo (1991) and others. Part of this literature is surveyed by Sala-i-Martin (1990), Helpman (1992), and Lucas (1993). See also Grossman and Helpman (1994), Romer (1994), and Solow (1994) for a review.

²There are few exceptions, however. Hung, Victor, and Blackburn (1993), Bovenberg and Smulders (1993), and Marrewijk, Ploeg, and Verbeek (1993) are examples of studies that attempt to incorporate environment into endogenous growth models. Our model structure is completely different from theirs. Besides they do not consider trade in their models.

are competitive objectives. This result is in contradiction with what many economists believe (e.g., see World Bank, 1992). Second, they tend to place emphasis on analyzing optimal growth only (even though economies do not behave optimally) rather than also considering a market driven dynamic equilibrium.³ Studies that use market analysis concentrate on the cost of environmental policy and ignore externalities which are at the heart of environmental economics.⁴

These gaps need to be filled. We need to have a better understanding of the linkages between innovations, trade, economic growth, and environmental quality. In other words, we are in need of a framework that integrates the theory of endogenous economic growth, the theory of international trade, and environmental economics. It should enable us to answer questions like the following. What are the implications of introducing environmental considerations in a standard endogenous growth model? Does environment slow or accelerate growth? What are the repercussions of trade? Does trade liberalization increase the long-run rate of economic growth? Does it improve or worsen the quality of the environment? Is trade welfare improving as it is oftentimes true in the absence of environmental externalities? Faced with environmental externalities, how can an economy optimally innovate and grow over time? Is a competitive equilibrium Pareto optimal and, if not, what are the policy implications? Are there first-best policies? If first best policies are not available, would there be second-best policies?

This paper attempts to model the link between innovations, trade, growth, and environmental

³Examples from this category are: Keeler, Spence, and Zechkauser (1971); D'Arge and Kogiku (1972); Gruuver (1976); Krautkraemer (1985); and Nordhaus (1991a, 1991b, 1992, 1993). An exception is Tahvonon and Kuuluvainen (1993) who analyze competitive equilibrium. In their model, however, technological change and trade issues are ignored.

⁴Examples are: Jorgenson and Wilcoxon (1990a, 1990b, 1993a, 1993b), Blitzer et al. (1993), Manne and Richels (1990), Burniaux et al. (1992). There is also a growing literature on the empirical aspects of growth and environment nexus. (See for example Grossman and Krueger (1993, 1994), Skafik and Bandyopadhyay, 1992). One major limitation of this work is that the estimated relationship is not derivable from a theoretical model.

quality. For this purpose we develop a multi-sectoral endogenous growth model that can be used to address the questions raised above. The model is in the tradition of the new growth theory specially the recent work of Grossman and Helpman (1991a, 1991b), Romer (1989, 1990), and Rivera-Batiz and Romer (1991). It has the following features. First, the model depicts a small open economy. There are two traded goods and all factors of production are not traded internationally. Second, technological change expands the range of intermediate inputs available in the market and is generated endogenously. There are also technological spillovers that facilitate invention of new designs. Third, inventors are granted infinitely-lived patents and thereby earn monopoly profits. Fourth, the model incorporates the welfare effects of environmental quality and its relation to pollution and abatement activities. Fifth, it permits analyzing the effects of environmental policy and other policies on economic growth.

The presence of environmental externalities makes a difference in the results that emerge from standard endogenous growth models. Growth models which ignore the effects of the environment on welfare produce different growth rates than those that incorporate environmental externalities. Whether these growth rates are smaller or larger depends on the elasticity of intertemporal substitution. The equilibrium and optimal growth rates are, in general, different. This is an expected result in view of the many externalities considered. Unlike other models of endogenous technological change with knowledge spillovers, which suggest the competitive equilibrium growth rate is always below the Pareto optimal one, and in contrast to environment-growth models, which put the decentralized growth rate above the optimal rate, the results of our model depend on certain conditions. If they are not satisfied, the opposite result will be obtained. Naturally, the policy implications are different in each case. In one knife-edge case there is no need for policy intervention.

We explore several policies that could align the two growth paths. Whether trade enhances or frustrates growth depends on the relation between factor intensities of the two final output sectors and that of the research and development sector and the relative abundance of the factor that R&D uses more intensively. The effects of trade on environment and welfare are ambiguous. They depend on a number of conditions that will be shown.

The paper is organized as follows. The model is presented in Section II. The "competitive" equilibrium and the determinants of sustained growth are derived in Section III. We also study the effects of consumers' attitude toward the environment on growth. In Section IV, the solution to a social planner's problem is discussed and compared to the market solution. We also derive the conditions under which the two solutions are different. Section V focuses on how intervention can secure optimal allocations of resources.

The model of Section II assumes firms cannot control pollution even if they wish to. Section VI extends this model to incorporate the ability of firms to control pollution. In this model there is an effluent charge on pollution emitted into the environment. Technological knowledge reduces the cost of controlling pollution. Because of the difficulty of finding analytical solutions, we solve the model numerically. In Section VII we summarize our results and provide concluding remarks.

II. The Model

The economy is small in the sense of being unable to influence its terms of trade. It produces two commodities using two primary factors of production, a set of differentiated intermediate inputs, and new designs to produce these differentiated inputs. While the two commodities are allowed to freely move across the borders of this country, primary and intermediate inputs are immobile. New designs

are assumed to be nontradable. We will also assume that exchange of knowledge is not possible.

Consumers. There are many identical infinitely-lived consumers who get utility from the two traded goods and the environment. Momentary utility of a representative consumer is given by⁵

$$U_t = \begin{cases} \frac{(C_y^\phi C_z^{1-\phi} Q^\mu)^{1-\sigma} - 1}{1-\sigma}, & \text{for } 0 < \sigma < \infty, \sigma \neq 1 \\ \phi \log C_y + (1-\phi) \log C_z + \mu \log Q, & \text{for } \sigma = 1 \end{cases} \quad (1)$$

$$0 \leq \phi \leq 1, \quad \mu \geq 0, \quad \phi(1-\sigma) < 1, \quad \mu(1-\sigma) < 1,$$

where C_i is consumption of commodity i ($i = Z, Y$) and Q is a variable measuring the quality of the environment and will be described in more details later. Throughout this paper all Greek letters and A 's are parameters. All other variables should be thought of as functions of time unless otherwise noted. We drop the time symbol to simplify the exposition. Consumers are endowed with two primary factors of production, capital (K) and labor (L) whose supply is fixed every period⁶.

Final output sectors. There are two sectors that produce final output. Each sector consists of a large number of identical firms. At the beginning of each period they rent labor and capital from consumers, and a set of differentiated inputs from the intermediate inputs sectors. Production functions of the two traded goods are given by

$$Y = A_y K_y^{\alpha_1} L_y^{\alpha_2} D_y^{\alpha_3}, \quad A_y > 0, \quad \sum_{i=1}^3 \alpha_i = 1, \quad \alpha_i > 0, \quad i = 1, 2, 3 \quad (2)$$

⁵This utility function exhibits the following properties (i) the elasticity of the marginal rate of substitution between consumption and environmental quality with respect to consumption, $[\partial \log (U_Q/U_{c_i}) / \partial \log C_i]$, is equal to one; (ii) the elasticity of the marginal utility of consuming commodity i is constant; (iii) the elasticity of the marginal utility of environmental quality is constant and equal to $1-\mu(1-\sigma)$; and (iv) it satisfies Inada conditions: $\lim_{C_i \rightarrow 0} U_{c_i} = \infty$, $\lim_{C_i \rightarrow \infty} U_{c_i} = 0$, $\lim_{Q \rightarrow 0} U_Q = \infty$, and $\lim_{Q \rightarrow \infty} U_Q = 0$. This is the only functional form compatible with steady state.

⁶Elbasha (1995) analyzes the implications of environmental externalities in three classes of endogenous growth models that allow factor accumulation. All these are, however, closed economy models.

$$Z = A_z K_z^{\beta_1} L_z^{\beta_2} D_z^{\beta_3}, \quad A_z > 0, \quad \sum_{i=1}^3 \beta_i = 1, \quad \beta_i > 0, \quad i = 1, 2, 3, \quad (3)$$

where K_i is capital used in producing commodity i , L_i is labor used in the production of good i , and D_i ($i = y, z$) denotes an index of differentiated inputs and is determined according to⁷

$$D_i = \left[\int_0^M X_i(j)^\delta dj \right]^{1/\delta}, \quad 0 < \delta < 1, \quad (4)$$

where $M(t)$ denotes the measure (number) of differentiated products available at time t and $X(j)$ is the amount of differentiated input j . The set of brands available at time t , $\{i: i \in [0, M(t)]\}$, is assumed to be continuous. We also assume that both commodities Y and Z have the same intensity in D (i.e. $\alpha_3 = \beta_3$). This, together with the constant returns to scale restrictions, imply $\alpha_1 + \alpha_2 = \beta_1 + \beta_2$.

Intermediate inputs Sectors. Each brand $j \in [0, M(t)]$ of differentiated inputs is produced by a single firm. Firms have to obtain a license to use the blueprints for producing a brand from the R&D sector before production starts. Once the license is acquired a firm can produce as much quantity of $X(j)$ it wishes according to the following Cobb-Douglas technology

$$X(j) = A_x [K_x(j)]^\eta [L_x(j)]^{1-\eta}, \quad A_x > 0, \quad 1 > \eta > 0, \quad j \in [0, M], \quad (5)$$

where $L_x(j)$ and $K_x(j)$ denote labor and capital used to produce $X(j)$, respectively. The above specification restricts the technology to be the same in all intermediate inputs sectors.

R&D sector. Research and development are undertaken in this sector. Firms use labor, capital, and a public good (knowledge capital) to produce new blueprints and thereby add to the set of available

⁷This is the famous Dixit and Stiglitz's (1977) formulation of horizontal product differentiation. Ethier (1982) reinterpreted equation (5) as a production function instead of a utility function as in Dixit and Stiglitz (1977).

brands. So, product development in the R&D sector evolves according to

$$\dot{M} = A_m K_m^\theta L_m^{1-\theta} M, \quad A_m > 0, 1 > \theta > 0, \quad (6)$$

where a dot over a variable stands for the time derivative of that variable, K_m is capital, L_m is labor used in R&D sector, and M , the measure of differentiated inputs, is assumed to be proportional to knowledge capital. We choose units of measure appropriately such that the factor of proportionality is one.

Environmental quality. To avoid adding another state variable to the system, we model the quality of the environment as a flow variable. We offer two formulations. First, environmental quality is determined by the following geometric index

$$Q = A_Q E_y^{\epsilon_y} E_z^{\epsilon_z}, \quad A_Q > 0, \epsilon_y, \epsilon_z < 0, \quad (7)$$

where E_y and E_z denote total emissions from sectors Y and Z, respectively. Emission levels are assumed to be proportional to the respective aggregate quantities of Y and Z produced. One can think of Y as denoting agriculture which contaminates the water system and Z as industry which generates air pollution. The quality of the environment is, therefore, given by the inverse of the geometric index of water and air pollution. In the second approach, we assume that use of differentiated intermediate inputs generates pollution which impairs the ability of people to enjoy the quality of the environment. We choose the following functional form to describe this

$$Q = \left[\int_0^{M(t)} X(j)^\epsilon dj \right]^{-1/\epsilon}, \quad \epsilon > 0. \quad (7')$$

We assume agents are atomistic and take prices and the quality of the environment as given.

Market Structure. The markets for the two traded goods (Y and Z), labor, capital, and new designs from the R&D sector are perfectly competitive. However, each producer of a differentiated input sells its output in an imperfectly competitive market.

III. Equilibrium Analysis

We define equilibrium in the following way. An equilibrium is paths for prices and quantities such that

1. Consumers makes consumption and asset accumulation decisions treating prices, interest rate, and environmental quality as exogenous functions of time.
2. Final output producers choose quantities of labor and capital taking output prices, prices of primary and intermediate factors, and the measure of intermediate inputs as given.
3. Intermediate inputs producers maximize profits taking as given the price of labor and capital, final output prices, the downward-sloping demand for their products, the number of differentiated inputs, and the initial cost of obtaining a design.
4. Firms in the R&D sector choose labor and capital to create new designs taking as given the price of new designs, prices of primary factors, and the stock of knowledge as given.
5. All markets clear.

We assume that all agents have perfect foresight so that at each moment of time the entire path of prices is known. We will also assume that our small economy operates within its cone of diversification ruling out specialization in the production of Z and Y.

Profit maximization in the final good sectors requires equating unit costs to prices. That is⁸,

⁸Intermediate inputs producers cannot price discriminate between sectors because the price elasticities of demand are the same in the two sectors, see equation (12) below. The unit cost functions in equations (8) and (9) are derived as $\min w_L L_i + w_K K_i + p_d D_i$ s.t. (2) and $Y = 1$ for $i = y$, and s.t. (3) and $Z = 1$ for $i = z$. That in equation (10) is

$$p_y = w_k^{\alpha_1} w_L^{\alpha_2} p_d^{\alpha_3} \quad (8)$$

$$p_z = w_k^{\beta_1} w_L^{\beta_2} p_d^{\beta_3} \quad (9)$$

$$p_d = \left[\int_0^M p_x(j)^{\frac{\delta}{\delta-1}} dj \right]^{\frac{\delta-1}{\delta}}, \quad (10)$$

where w_k denotes the price of capital, w_L is price of labor, p_d is price of the index D , $p_x(j)$ is price of intermediate inputs j , and p_y and p_z are prices of commodity Y and Z , respectively. Notice that in deriving the unit cost functions we have chosen the constants of the production functions appropriately.

Equilibrium in the R&D sector requires equating the price of a design to its unit cost. That is,

$$p_m = \frac{w_k^\theta w_L^{1-\theta}}{A'_m M}, \quad (11)$$

where p_m is the price of a new design and $A'_m = A_m \theta^\theta (1-\theta)^{1-\theta}$.

Applying Shephard's lemma to the unit cost function in equation (10), we can derive the demand for $X_k(j)$ as

$$X_i(j) = p_x(j)^{\frac{1}{\delta-1}} D_i \left[\int_0^M p_x(s)^{\frac{\delta}{\delta-1}} ds \right]^{\frac{1}{\delta}}, \quad i = y, z, j \in [0, M]. \quad (12)$$

Each firm in the intermediate goods sectors, acting monopolistically, maximizes profits taking into

obtained by minimizing $\int_0^M p(i) X(i) di$ s.t. (4) and $D = 1$.

account the demand functions in equation (12). Profits are maximized by following the mark-up over marginal cost pricing rule

$$p_x(j) = \frac{w_k^\eta w_L^{1-\eta}}{\delta}, \quad \forall j \in [0, M]. \quad (13)$$

Therefore, price, quantity, and hence the level of profits are the same for all firms operating in the intermediate inputs sectors. Using this fact in equation (10) yields

$$p_d = p_x M^{\frac{\delta-1}{\delta}}, \quad (10')$$

where p_x denotes the common equilibrium price in the intermediate inputs sectors.

The cost functions in equations (8), (9), (10'), and (13) can be solved for input prices. The solutions for the price of labor and capital are given by

$$w_L = p_y \left(\frac{p_y}{p_x} \right)^{\frac{\alpha_1 + \alpha_3 \eta}{\beta_1 - \alpha_1}} \delta^{\alpha_3} M^{\frac{\alpha_3(1-\delta)}{\delta}} \quad (14)$$

$$w_k = p_y \left(\frac{p_y}{p_x} \right)^{\frac{\alpha_1 + \alpha_3 \eta - 1}{\beta_1 - \alpha_1}} \delta^{\alpha_3} M^{\frac{\alpha_3(1-\delta)}{\delta}}. \quad (15)$$

In this equilibrium we will assume that world prices and the rate of innovation, M/M , are constant over time. Hence, equations (14) and (15) imply

$$\frac{\dot{w}_L}{w_L} = \frac{\dot{w}_k}{w_k} = \frac{\alpha_3(1-\delta)}{\delta} g \quad (16)$$

where $g = M/M$. This, together with equation (11), yields

$$\frac{\dot{p}_m}{p_m} = \frac{[\alpha_3(1 - \delta) - \delta]}{\delta} g. \quad (17)$$

From the unit cost functions, using Shephard's lemma, we obtain the following input-output coefficients:

$$\begin{aligned} b_{ky} &= \alpha_1 \frac{p_y}{w_k}, \quad b_{kz} = \beta_1 \frac{p_z}{w_k}, \quad b_{kx} = \eta \delta \frac{p_x}{w_k}, \quad b_{km} = \theta \frac{p_m}{w_k}, \quad b_{ly} = \alpha_2 \frac{p_y}{w_L}, \\ b_{lx} &= \beta_2 \frac{p_x}{w_L}, \quad b_{lz} = (1-\eta)\delta \frac{p_x}{w_L}, \quad b_{lm} = (1-\theta) \frac{p_m}{w_L}, \quad b_{xy} = \alpha_3 \frac{p_y}{p_x}, \quad b_{xz} = \beta_3 \frac{p_z}{p_x} \end{aligned} \quad (18)$$

where b_{ij} denotes per unit input i used in the production of good j , $i = k, L, x$ and $j = y, z, x, m$. Substituting these in the resource constraints, making use of the identity $p_x X M \equiv p_d(D_y + D_z) = \alpha_3 p_y Y + \beta_3 p_z Z$, and rearranging gives

$$(\alpha_1 + \delta \eta \alpha_3) p_y Y + (\beta_1 + \delta \eta \beta_3) p_z Z + \theta p_m M g = w_k K \quad (19)$$

$$[\alpha_2 + \delta(1-\eta)\alpha_3] p_y Y + [\beta_2 + \delta(1-\eta)\beta_3] p_z Z + (1-\theta) p_m M g = w_L L. \quad (20)$$

Since g , p_z and p_y are constant, equations (19) and (20) suggest that both Y and Z grow at the same rate of growth as that of w_L and w_k . That is,

$$\frac{\dot{Y}}{Y} = \frac{\dot{Z}}{Z} = \frac{\alpha_3(1-\delta)}{\delta} g. \quad (21)$$

Adding equations (19) and (20) and making use of some of the restrictions on the parameters yields

$$[1 - \alpha_3(1 - \delta)](p_z Z + p_y Y) = w_K K + w_L L - p_m M g \quad (22)$$

Because firms are allowed to freely enter into and exit from R&D, in equilibrium, the price of a new design is equivalent to the value of a firm in the intermediate inputs sectors. To maintain asset market equilibrium, the rate of return from holding equities (i.e. dividends plus changes in the value of the firms) should be equal to the rate of return on a one period loan. Thus, in equilibrium the following no-arbitrage condition is satisfied

$$\frac{\pi}{p_m} + \frac{\dot{p}_m}{p_m} = r, \quad (23)$$

where π denotes the profit level of a firm in the intermediate inputs sectors, and r is the rate of interest on loans. Using the fact that $\pi/p_m = (1-\delta)p_x X/p_m = (1-\delta)p_d D/Mp_m = (1-\delta)\alpha_3(p_y Y + p_z Z)/Mp_m$, with equations (17) and (22), we can rewrite the above condition as

$$\frac{(1-\delta)\alpha_3}{[1-\alpha_3(1-\delta)]} \frac{(w_L L + w_K K - p_m M g)}{M p_m} + \left[\frac{\alpha_3(1-\delta)}{\delta} - 1 \right] g = r. \quad (23')$$

Utilizing equation (1), the consumer's indirect utility function is

$$V(E, p_y, p_z, Q) = \frac{[(EQ^\mu)/p_y^\phi p_z^{1-\phi}]^{1-\sigma} - 1}{1-\sigma} =$$

$$\text{Max} \frac{(C_y^\phi C_z^{1-\phi} Q^\mu)^{1-\sigma} - 1}{1-\sigma} \text{ s.t. } p_y C_y + p_z C_z = E,$$

where E stands for expenditure. The solution to the consumer's problem is given by solving the following dynamic problem

$$\begin{aligned} \text{Max}_{\{E(t)\}} \quad & \int_0^{\infty} V(E, p_y, p_z, Q) e^{-\rho t} dt \\ \text{s.t.} \quad & \dot{E} + \dot{a}(t) = r a(t) + w_K K + w_L L \end{aligned}$$

where $a(t)$ denotes nonhuman wealth at time t . Application of the Maximum Principles results in the following relation

$$\sigma \frac{\dot{E}}{E} - \mu(1-\sigma) \frac{\dot{Q}}{Q} = r - \rho. \quad (25)$$

Due to the nature of the utility function, and because consumers have perfect information and rational expectations (perfect foresight in this case), changes in the quality of the environment affect the path of consumption over time. It is interesting to note that even though consumers take Q as given, its evolution affects their behavior. Notice that if $\sigma = 1$ (i.e. the utility is of the logarithmic form) or if the utility is additively separable in Q , the second term in equation (25) will disappear and so the consumption path will not be affected by Q .

We assume that our small country cannot lend or borrow from the outside world. Hence, trade is always in balance

$$E = p_y Y + p_z Z. \quad (26)$$

Differentiating equation (26) with respect to time and making use of equation (21) gives

$$\frac{\dot{E}}{E} = \frac{\alpha_3(1-\delta)}{\delta} g. \quad (27)$$

We can also combine equations (7) or (7') and (21) to obtain

$$\frac{\dot{Q}}{Q} = \frac{(\epsilon_y + \epsilon_x) \alpha_3 (1 - \delta)}{\delta} g. \quad (28)$$

if equation (7) applies or

$$\frac{\dot{Q}}{Q} = \frac{(\epsilon - 1)}{\epsilon} g \quad (28')$$

when (7') is the relevant equation. Substituting equations (27) and (28) into equation (25) and rearranging yields

$$r = \rho + \Psi \frac{\alpha_3 (1 - \delta)}{\delta} g \quad (29)$$

where $\Psi = \sigma - \mu(1 - \sigma)(\epsilon_y + \epsilon_x)$. If instead we use equation (28') we get $r = \rho + \Psi' \alpha_3 (1 - \delta) g / \delta$, where $\Psi' = \sigma - \mu(1 - \sigma)(\epsilon - 1) \delta / (1 - \delta) \epsilon \alpha_3$. Solving for w_L / w_K from equations (14) and (15) and combining equations (11), (23'), and (29) and rearranging gives the growth rate of innovation in terms of the parameters of the model, endowments, and exogenous variables

$$g = \frac{\Delta A_m' \left(\frac{P_y}{P_x} \right)^{\frac{\theta}{\beta_1 - \alpha_1}} \left[\left(\frac{P_y}{P_x} \right)^{\alpha_1 - \beta_1} K + L \right] - \rho}{1 + \Delta + \frac{\alpha_3 (1 - \delta)}{\delta} (\Psi - 1)} \quad (30)$$

where $\Delta = \alpha_3 (1 - \delta) / [1 - \alpha_3 (1 - \delta)]$. If equation (7') applies, we will have Ψ' instead of Ψ in the growth formula. It should be noted that the integral in the consumer's utility function is always finite provided $\alpha_3 (1 - \delta) (1 - \Psi) g / \delta < \rho$. The transversality condition associated with the consumer's problem ensures the satisfaction of this inequality. The fact that we looked only for interior solution to the R&D sector

problem implicitly imposes a restriction on the growth formula in equation (30): growth has to be strictly positive. We assume our parameters satisfy this and the condition required for boundedness of the utility function. Both the numerator and denominator in equation (30) are taken to be positive.

In this model the effects of environmental externalities are captured by the parameters $-\mu(\epsilon_y + \epsilon_z)$ if equation (7) applies or $\mu(\epsilon-1)\delta/\epsilon\alpha_3(1-\delta)$ if equation (7') is the relevant equation. We adopt the assumption that the effects of environmental externalities are mild relative to expenditure on consumption i.e. $1 > -\mu(\epsilon_y + \epsilon_z)$ if equation (7) applies and $1 > \mu(\epsilon-1)\delta/\epsilon\alpha_3(1-\delta)$ if we have equation (7') instead. In other words, we assume consumers value consumption more than environmental quality .

Claim. *If consumers value consumption more than environmental quality, $\Psi > 0$, and Ψ, Ψ' is greater, equal to, or less than one as σ is greater, equal to, or less than one; respectively.*

Proof. Rearrange the formulas for Ψ and Ψ' the result is obvious.

The comparative static results of the growth rate are summarized by the following propositions.

Proposition 1. *Growth is higher (i) the larger is the country's endowment of K and L, (ii) the more productive is R&D (higher A'_m), (iii) the smaller the rate of time preference, (iv) the larger the elasticity of intertemporal substitution ($1/\sigma$), or (v) the smaller the elasticity of substitution (lower δ) provided $\Psi \leq 1$ ⁹.*

Proof. The denominator in equation (30) is positive. Differentiating that equation with respect to the relevant variable we get (i) $\partial g/\partial K = A'_m(p_y/p_z)^{(1-\theta)/(\alpha-1-\beta)} / (\text{denominator}) > 0$, $\partial g/\partial L = A'_m(p_y/p_z)^{-\theta(\alpha-1-\beta)} / (\text{denominator}) > 0$; (ii) $\partial g/\partial A'_m = 1/(\text{denominator}) > 0$; (iii) $\partial g/\partial \rho = -1/(\text{denominator}) <$

⁹According to Lerner (1934) price minus marginal cost divided by price measures the degree of market power. In our case, this is given by $1 - \delta$. Therefore, an increase in the degree of market power (i.e. lower δ) increases growth.

0; (iv) $\partial g/\partial \sigma = [-g/(\text{denominator})^2] \partial \Psi/\partial \sigma$. But $\partial \Psi/\partial \sigma > 0$. hence, $\partial g/\partial \sigma < 0$; (v) $\partial g/\partial \delta = [\text{denominator} (\text{numerator} - \Delta \Omega) + \alpha_3(\Psi-1)/\delta^2]/(\text{denominator})^2$, where $\Omega = (p_y/p_z)^{(1-\theta)/(\alpha_1-\beta_1)} K + (p_y/p_z)^{-\theta/(\alpha_1-\beta_1)} L$. But $\partial \Delta/\partial \delta < 0$ and $(\text{numerator} - \Delta \Omega) > 0$. Hence, $\partial g/\partial \delta < 0$.

Proposition 2. *With the source of environmental externalities as described by equation (7), environmental quality decays at a constant rate along the balanced growth path. If instead pollution is governed by equation (7'), environmental quality decays, stays constant, or improves at a constant rate as ϵ is less, equal to, or greater than one; respectively.*

Proof. See equation (28) and (28').

III.1 The effects of environmental externalities on growth

Let the quality of the environment be given by equation (7). Then, taking environment into account slows growth if the elasticity of intertemporal substitution ($1/\sigma$) is greater than one. This can easily be seen from the growth formula in equation (30). If agents ignore the effects of the environment (i.e. $\mu = 0$), the denominator of equation (30) will be smaller and hence growth will be higher. This result implies that countries in which consumers care more about the effects of environmental externalities grow faster than those which don't. Moreover, growth is lower, the more profound are the effects of the environment on consumer's utility (i.e. lower μ), provided $\sigma < 1$. If $\sigma > 1$, the opposite result will be obtained: growth varies positively with agents care about the effects of environment. It may be interesting to note that if $\sigma = 1$ (i.e. the case of a logarithmic utility) or if the utility function is additively separable, the environment doesn't affect the growth rate under the competitive conditions assumed. Changes in the elasticities of environmental quality with respect to pollution levels (ϵ_y and ϵ_z) have the opposite qualitative effects on growth compared to changes in μ . We have proved the following proposition.

Proposition 3. *Care about the environment slows, doesn't affect, or promotes growth if and only if the elasticity of intertemporal substitution ($1/\sigma$) is greater, equal to, or less than one; respectively. If the quality of the environment is given by equation (7'), the above results hold only if $\epsilon < 1$. When $\epsilon > 1$, we obtain the opposite qualitative result. If $\epsilon = 1$, environment does not affect growth.*

To get a feeling of the importance of incorporating environment in this endogenous growth model follow this simple numerical exercise. Let $\alpha_3(1-\delta)/\delta = 1$, $A'_m = 0.075$, $p_y = p_z = L = K = 1$, $\delta = 1/3$, $\epsilon_y + \epsilon_z = -1$, $\sigma = 1.8$, and $\rho = 0.025$. Choose $\mu = 0$ and use equation (30) to compute g as 2.17%. If $\mu = 0.9$, then $g = 3.16\%$. Therefore, about 1% difference in growth rates across countries can be explained by concern about the environment. Needless to emphasize, we could have chosen the parameters in a way that would magnify this disparity.

III.2 The terms of trade effects

Assume that commodity Y is exported and Z is imported. Normalize the initial terms of trade to one, and to neutralize the effects of endowments, suppose $K = L$. Then we have the following proposition.

Proposition 4. *Let R&D be capital intensive (i.e. $\theta > 1/2$). Then an improvement in the terms of trade (i.e. higher p_y/p_z) enhances (retards) growth if Y is less (more) capital intensive than Z.*

Proof. If we differentiate equation (30) and use the above restrictions we arrive at: $\text{sign}[\partial g/\partial(p_y/p_z)] = \text{sign}[(\alpha_1 - \beta_1)(\theta - 1/2)]$. The proof follows immediately.

The intuition behind this result is simple. Stolper-Samuelson theorem suggests a fall in w_k and a rise in w_L as a result of the rise in p_y/p_z if Y is less capital intensive than Z. Hence the demand for capital in R&D (which is capital intensive) increases and so does the growth rate. The above result suggests that improvements in the terms of trade boosts growth only if whatever factor intensity R&D

has, exportables have less of it than importables. This can be seen more clearly if we consider the two polar cases (i) R&D is extremely labor intensive (i.e $\theta = 0$) and (ii) R&D is extremely capital intensive (i.e. $\theta = 1$). Substitute these values of θ in the growth formula and the result would become transparent.

Now let us relax our assumption on endowments and initial terms of trade. We obtain the following more general result.

Proposition 5. *If exportables are more (less) capital intensive than importables, then an improvement in the terms of trade promotes (retards) growth if and only if the capital-labor ratio in the R&D sector is less (more) than the endowments ratio of capital to labor.*

Proof. Differentiating the growth rate with respect to the terms of trade we get:
 $\text{sign}[\partial g/\partial(p_y/p_z)] = \text{sign}\{(\alpha_1 - \beta_1) [K(p_y/p_z)^{1/(\alpha_1 - \beta_1)} - \theta/(1-\theta)]\}$. But in equilibrium, $(p_y/p_z)^{1/(\alpha_1 - \beta_1)} = w_L/w_k$ and $\theta = w_k K_m$ and $w_L L_m = (1-\theta)$. Therefore, $\text{sign}[\partial g/\partial(p_y/p_z)] = \text{sign}[(\alpha_1 - \beta_1) (K/L - K_m/L_m)]$.

This result suggests an easy empirical test for the terms of trade effects on growth. It requires data on factor intensities in the import, export, and R&D sectors and the scarcity of capital relative to labor.

III.3 The effects of trade on growth

There are at least two approaches which we can follow in order to analyze the effects of trade on growth. The first approach requires computing both the autarky and trade equilibria and comparing the growth rates. The second approach utilizes some results from trade theory about the properties of the two equilibria to investigate the effects of trade. Trade theory tells us that the relative price of the imported commodity (suppose it is Z) is always higher in autarky than in the free trade

equilibrium. Then the effects of opening this economy to international trade can be investigated by analyzing the effects of a rise in the relative price (p_y/p_z) on the equilibrium studied above. While the first approach is more direct and quantitatively oriented, the second one is more appealing because it doesn't require computing the autarky equilibrium in order to derive qualitative results about the effects of different trade regimes. Since in this section we are interested only in qualitative results we opt for the second approach.¹⁰ Then according to Proposition 5, trade enhances growth if exportables are more (less) capital intensive than importables and the post trade capital-labor ratio in the R&D sector is less (more) than the ratio of the endowments of capital to labor.

III.4 The effects of trade on environment

Like that on growth, the effects of trade on the environment can be analyzed by considering a rise in the relative price p_y/p_z . Using equation (7), the quality of the environment can be written as

$$Q = A_Q \tilde{Y}^{\epsilon_y} \tilde{Z}^{\epsilon_z} M^{\frac{(\epsilon_y + \epsilon_z)(1-\delta)\alpha_3}{\delta}} \quad (7'')$$

where $\tilde{Y} = YM^{(1-\delta)\alpha_3/\delta}$ and $\tilde{Z} = ZM^{(1-\delta)\alpha_3/\delta}$.

Differentiating equation (7'') with respect to p_y and converting the resulting equation in elasticity form we arrive at

$$\zeta_{QY} = [\epsilon_y \zeta_{YY} + \epsilon_z \zeta_{ZY} + (\epsilon_y + \epsilon_z) \frac{(1-\delta)\alpha_3}{\delta} \zeta_{MY}] \quad (31)$$

where ζ_{iy} is commodity Y's price elasticity of variable i , $i = Z, Y, Q$. From equations (14), (15), (19), and (20) we can derive expressions for ζ_{YY} , ζ_{ZY} , and ζ_{MY} . The signs of these expressions are, in general, ambiguous. Intuition suggests ζ_{YY} is positive and ζ_{ZY} is negative. Even if this is true the sign

¹⁰In the numerical exercise of Section VI, we follow the first approach.

of ζ_{Oy} is still ambiguous. Notice that the last term involves ζ_{my} which may be positive or negative. Notice also that this term ($\zeta_{my} = t g \zeta_{gy}$) becomes dominant as time goes on. Therefore, if ζ_{my} is positive (the case where trade enhances growth), in the long-run trade worsens the quality of the environment. If, however, this country decides to open its borders for trade in period zero, then trade improves the quality of the environment if and only if $\zeta_{yy} < -\epsilon_z / \epsilon_y \zeta_{zy}$. But the environment will continue to deteriorate at a higher or a lower rate thereafter depending on whether trade enhances or retards growth. So, the time at which a country opens its boarders to trade also matters. The second formulation of the environment also gives rise to ambiguous results.

III.5 The welfare effects of trade: Gains or losses?

In this equilibrium trade has two opposing effects on welfare. On one hand we have the usual static gains from trade. Using Roy's identity, the fall in the price of the imported good can be shown to result in higher utility. It may also have positive dynamic effects on welfare through the growth channel. On the other hand trade may worsen the quality of the environment and hence negatively affect welfare. The overall welfare effect of trade is, therefore, ambiguous. It depends on which effect is more dominating. In a later exercise we will use numerical values to investigate those effects.

IV. The social planner's problem

The social planner's problem for this country can be written as

$$\text{Max } \int_0^{\infty} V(E, p_y, p_z, Q) e^{-\rho t} dt$$

s. t.

$$(2), (3), (4), (5), (6), (7 \text{ or } 7'), (26)$$

$$X_y(j) + X_z(j) = X(j), j \in [0, M]$$

$$L_y + L_z + \int_0^M L_x(i) di + L_m = L$$

$$K_y + K_z + \int_0^M K_x(i) di + K_m = K$$

$M(0) > 0$ given.

The optimal growth rate of innovation is given by (the derivations are in Appendix I)

$$g_m = \frac{\frac{\alpha_3(1-\delta)}{\delta} A_m' \left(\frac{P_y}{P_z}\right)^{\theta/(\beta_1-\alpha_1)} \left[\left(\frac{P_y}{P_z}\right)^{1/(\alpha_1-\beta_1)} K + L\right] - \rho}{\frac{\alpha_3(1-\delta)}{\delta} \Psi} \quad (32)$$

if equation (7) applies or

$$g_m = \frac{\Delta' A_m' \left(\frac{P_y}{P_z}\right)^{\theta/(\beta_1-\alpha_1)} \left[\left(\frac{P_y}{P_z}\right)^{1/(\alpha_1-\beta_1)} K + L\right] - \rho}{\Delta' + \frac{\alpha_3(1-\delta)}{\delta} (\Psi' - 1)} \quad (32')$$

where $\Delta' = [(\epsilon-1)/\epsilon + \alpha_3(1-\delta)/\delta]/(1-\mu)$, if equation (7') is the relevant equation.

Proposition 6. *The optimal growth rate has the following properties. It is higher (i) the larger the country's endowment of labor and capital, (ii) the more productive is R&D, (iii) the smaller the rate of time preference, (iv) the less consumers value the effects of the environment (lower μ) provided $\sigma < 1$, (v) the larger the intertemporal elasticity of substitution (smaller σ), or (vi) the smaller the elasticity of substitution between any two differentiated products (smaller δ).*

Moreover, what we have said about the terms of trade effects in competitive equilibrium also applies here.

If $\alpha_3(1-\delta)/\delta = 1$, the equilibrium presented above is of the balanced growth type in which Y, Z, and M grow at the same rate. This is obvious from equations (21): if $\alpha_3(1-\delta)/\delta = 1$, we will have

Y and Z growing at the rate g . If this condition is satisfied and if equation (7) applies, we will have $g < g_m$ i.e. the decentralized growth rate is always smaller than the Pareto optimal one. To see that we just need to note that $0 < \Delta < \alpha_3(1-\delta)/\delta = 1$. To prove that $\Delta < \alpha_3(1-\delta)/\delta$, suppose the opposite: $\Delta \geq \alpha_3(1-\delta)/\delta$. This implies $\delta \geq 1 - \alpha_3(1-\delta)$, or $\alpha_3 \geq 1$ an obvious contradiction. Therefore, equation (30) has a bigger denominator and a smaller numerator than equation (32). This also suggests that if $\Gamma \equiv 1 + \Delta - \alpha_3(1-\delta)/\delta \geq 0$, $g < g_m$. This implies that for the market rate to be higher than the Pareto optimal rate a necessary condition would be $\Gamma < 0$. But $\partial\Gamma/\partial\delta < 0$. So for the market rate to be higher than the optimal rate, it is necessary to have strong monopoly power. More generally we have the following proposition.

Proposition 7. *The decentralized equilibrium growth rate is less than (equal to) [greater than] the Pareto optimal rate if and only if zero is less than (equal to) [greater than] $\Gamma[\alpha_3(1-\delta)\Omega/\delta - \rho] + \alpha_3(1-\delta)\Omega\Psi(1-\Gamma)/\delta$.*

Proof. Subtract equation (32) from equation (30). You will get $\text{sign}(g - g_m) = -\text{sign}\{\Gamma[\alpha_3(1-\delta)\Omega/\delta - \rho] + \alpha_3(1-\delta)\Omega\Psi(1-\Gamma)/\delta\}$.

Proposition (7) reveals that the market rate tends to be bigger than the optimal rate the smaller is δ and Ψ . But Ψ is smaller the more strong are the effects of environmental externalities on consumers welfare i.e. the bigger is $-\mu(\epsilon_y + \epsilon_z)$ provided $\sigma > 1$. Therefore, the market rate is bigger than the optimal rate, the larger is the degree of monopoly power and the more important are environmental externalities.

Many studies in the literature are concerned about whether growth and the environment are substitutes or complements. Because they implicitly view environment as an end in itself, their natural conclusion would be growth should grind to a halt if it harms the environment. In this paper and

economics more generally, neither growth nor the environment are ends in themselves, but they are means to achieve an end (i.e. enhance welfare). So, even if (as we specify here) growth and environment are substitutes (see equation (7)), the above proposition tells us how it is possible to have the competitive growth rate being below the optimal rate and so optimal preservation of the environment requires measures to enhance growth. We can look at this issue from a different angle. As we have shown earlier, if $\sigma > 1$, then growth varies positively with μ . In other words, the important implication is valuing the environment and growth go hand in hand.

The second approach to the environment teaches a very important lesson about the relationship between innovation, growth, and environmental quality. Technological change in this economy enables agents to use less and less of the dirty intermediate inputs and so, depending on whether these intermediate inputs substitute perfectly in generating pollution, the quality of the environment can be sustained at a constant rate.

V. Policy Implications

The divergence of the decentralized equilibrium growth path from the Pareto optimal one calls for government intervention. As expected, however, not all kinds of government intervention are desirable. In this section we attempt to find some 'desirable' policy instruments as well as showing the danger behind choosing the wrong type and magnitude of policy variables. We hasten to note that because the relationship between the competitive and optimal growth path is ambiguous it is easy to make mistakes in choosing a desirable policy instrument. To elaborate, suppose the optimal growth rate is below the decentralized growth rate. Then all growth-boosting policies are among the wrong choice set.

For the rest of the paper we analyze only the case where the environment is given by equation (7). Our analyses in this section are restricted to the case of balanced growth equilibrium. For this purpose we take the condition $\alpha_3(1-\delta)/\delta = 1$ to be satisfied. As has been shown earlier, under this condition, the decentralized balanced growth path is always below the Pareto optimal path. This suggests that we should consider as candidates for 'desirable' policy instruments only those which boost growth. It is natural to look for first-best policies. These are by definition designed to remove all distortions. They include a subsidy to R&D sector to internalize the externality from knowledge creation, a subsidy to the intermediate inputs sector to equate marginal cost to prices, and an emission tax on final output producers to internalize pollution externalities. With optimal choice of levels of these taxes and subsidies, the optimal allocations can be attained through a decentralized competitive market driven equilibrium. Instead of analyzing first-best policies we will concentrate only on second-best policies. There are two reasons for this choice. First, in reality not all these instruments (four of them in this case) will be available for policy makers. There may be only a subset of them at their disposal. We are, therefore, left in the realm of second-best world. Second, if growth is the most important variable of interest, only one policy instrument is needed to align the two growth paths.

All the policies considered below are sustained through lump-sum transfers. We adopt the following strategy in calculating optimal policies. We introduce the policy change and compute the policy-ridden growth rate. Then we equate that rate with the optimal growth rate and solve for the optimal level of the policy variable.

(1) A subsidy to R&D. Suppose the government pays an ad valorem subsidy, χ_m , to the R&D sector per each new design. This has obvious immediate effects on growth since it increases \dot{M} . The optimal subsidy rate is given by

$$\chi_m = \frac{\Omega\Psi}{\Delta[\Omega(\Psi - 1) + \rho]} - 1. \quad (33)$$

(2) Trade policy: (i) An subsidy to Y. Let commodity Y be less capital intensive than Z and to make the calculations simple assume R&D is extremely capital intensive (i.e. $\theta = 1$). Suppose the government pays an ad valorem subsidy, χ_y , to the exporters of good Y. The objective of the subsidy would be to encourage more production of Y and less of Z (which is more capital intensive) so that less of it is produced domestically and consequently less of capital is used in Z and more of it will be available to R&D. An excise subsidy to the producers of Y would do the same. The optimal subsidy rate would be

$$\chi_y = \left(\frac{P_z}{P_y}\right) \left[\frac{(\Delta + \Psi)g_m + \rho - \Delta K^{\beta_1 - \alpha_1}}{\Delta L} \right] - 1. \quad (34)$$

(ii) A subsidy to the importers of Z can achieve the same objective and so is an excise tax on the production of Z. Let χ_z denote the subsidy rate. Its optimal rate should be set to

$$\chi_z = 1 - \left(\frac{P_y}{P_z}\right) \left[\frac{(\Delta + \Psi)g_m + \rho - \Delta K^{\alpha_1 - \beta_1}}{\Delta L} \right]. \quad (35)$$

(3) Tax on capital used in Z: this tax has the same qualitative effects as a fall in the price of good Z.

The optimal tax rate is given by

$$\chi_k = \left(\frac{P_z}{P_y}\right)^{1/\beta_1} \left[\frac{(\Delta + \Psi)g_m + \rho - \Delta K^{\beta_1 - \alpha_1}}{\Delta L} \right]^{\beta_1} - 1. \quad (36)$$

(4) Output subsidy to the intermediate inputs sector.

Suppose the government decides to pay an ad valorem subsidy to each producer of X_i . The optimal

subsidy rate would be

$$\lambda_x = \frac{(\rho + \Psi g_m)(1 - \alpha_3)}{(\Omega - g_m)(1 - \delta)\alpha_3 - \alpha_3(\rho + \Psi g_m)} - 1 \quad (37)$$

(5) Environmental policy. Since the objective is discourage production of Z and force it to release more capital resources to R&D we consider only the effect of a per unit emission tax, τ_z , on sector Z. The effects of this tax are similar to a fall in the price of Z. Optimal tax on emissions from Z should be set equal to

$$\tau_z = p_x - p_y \left[\frac{(\Delta + \Psi)g_m + \rho - \Delta K^{\alpha_1 - \beta_1}}{\Delta L} \right] \quad (38)$$

VI. Numerical Application

We maintain most of the specifications in the previous sections. The only change we make here is to introduce pollution abatement and its relation to innovation. Total amount of emissions of each sector is determined by

$$E_y = A_{ey} Y - E_{ey} \quad A_{ey} > 0 \quad (39)$$

$$E_z = A_{ez} Z - E_{ez} \quad A_{ez} > 0 \quad (40)$$

where E_{ck} is pollution controlled by sector k, k = y, z, and all other variables are defined earlier.

Abatement technologies are given by

$$E_{ei} = A_{ei} K_i^{v_{iy}} L_i^{v_{iz}} M_i, \quad v_{iy} > 0, \quad v_{iy} + v_{iz} < 1, \quad i = 1, 2 \quad (41)$$

$$E_{\alpha} = A_{\alpha} K_{\alpha}^{\nu_{1\alpha}} L_{\alpha}^{\nu_{2\alpha}} M, \quad \nu_{1\alpha} > 0, \nu_{1\alpha} + \nu_{2\alpha} < 1, i = 1, 2 \quad (42)$$

We assume abatement technologies in both sectors exhibits decreasing returns to scale. This specification gives rise to increasing marginal cost functions for controlling pollution. It also suggests that cost curves drift downward as more technological knowledge (higher M in this case) becomes available. This seems to be a plausible assumption that is implicit in the few studies which address the issue of pollution abatement and technical change (e.g., Dowling and White, 1986 and Magat, 1978).

Incorporating pollution control in this model adds more reality to our story but it doesn't come without cost. We couldn't find a closed form solution. We resort to numerical analysis. For this purpose we need to have numerical values for certain important parameters. Our choices for the parameters of the model are given in Table 1 in Appendix II. Several assumptions are hidden behind these values. First, $\alpha_3(1-\delta)/\delta = 1$. Thus the resulting equilibrium of the balanced growth type in which Y, Z, E, M, and 1/Q all grow at the same constant rate. Second, $\alpha_1 > \beta_1$ indicating that sector Y is more capital intensive than sector Z. Third, R&D is assumed to be capital intensive (since $\theta = 0.9 > 1 - \theta = 0.1$) whereas intermediate inputs sectors are labor intensive (because $\eta = 0.1$). Fourth, controlling pollution in sector Y requires a capital intensive technology whereas pollution abatement in sector Z is carried through a labor intensive technology.

Our previous analysis suggests that if Y is the imported commodity, the above restrictions imply trade promotes growth. It also suggests that the decentralized growth path is below the optimal path. Even though the current model is different (it is an extension of the previous model by incorporating pollution abatement), we conjecture these results will still hold. The model is solved, using Mathematica, for three steady state equilibria: autarky, trade, and Pareto optimal allocations.

The solutions for some variables of interest are given in Table 2 and their behavior overtime is depicted in Figures 1-6 in Appendix II. It should be noted that the thick lines represent Pareto optimal equilibrium, dashed lines stand for autarky equilibrium, and the thick lines denote trade equilibrium.

As expected trade promotes growth since the growth rate under trade is greater than that under autarky. Both growth rates are, however, smaller than the Pareto optimal rate. Trade worsens the quality of the environment. This can be seen more clearly from Fig. 2. The overall effects on welfare of opening the economy to trade are positive: welfare under trade is higher than welfare for a closed economy. Not surprisingly, welfare is maximized under Pareto equilibrium. Under trade the economy consumes more than it produces of commodity Y and so imports Y and exports Z.

Figures 7-8 depict the effects of environmental policy on growth. As it is clear from Figure 7, growth increases monotonically with pollution taxes on sector Y. This should be expected in light of the fact that Y is more capital intensive than Z, and the tax forces it to release more capital so as to be used in R&D which is capital intensive. An emission tax on sector Z has the opposite effect. This is clear from Figure 8.

VII. Conclusions

In this paper we have developed an endogenous growth model of a small open economy that incorporates the welfare effects of environmental quality and its relation to pollution and pollution abatement activities. Several conclusions emerge from the analysis of this model. First, long-run growth increases with (i) the country's endowments, (ii) the degree of openness provided whatever factor intensity R&D has, exportables have less of it than importables, and (iii) the degree of market power of patents' holders. Second, the effects of the environment on growth depend on the elasticity

of intertemporal substitution of consumption. If it is greater than one, environment slows growth. If it is, however, less than one, environment increases growth. It is worth mentioning that the empirical literature puts the elasticity of intertemporal substitution below one. Concerns about the environment can explain the large differences in growth rates across countries. Third, the effects of trade on environment and welfare are ambiguous. They depend on price elasticities of supply of traded goods, the terms of trade effects on growth, and pollution intensities. Numerical exercises, however, suggest trade worsens the quality of the environment but improves welfare. Fourth, because there is a positive externality from knowledge creation and negative externality from pollution, the competitive growth rate can be greater or smaller than the Pareto optimal rate. In one razor edge equilibrium, the two rates are equal. In the balanced growth equilibrium, the decentralized growth rate is below the Pareto optimal rate. The market rate of growth is likely to be greater than the optimal rate the larger the degree of monopoly power and the stronger the effects of environmental externalities. Many policy instruments can be used to align the two growth paths. The choice of the policy variable depends on the relationship between the Pareto optimal and market rates of innovation. If the former is greater than the latter, it is imperative to design policies that increase the profitability of R&D and decrease the profitability of sectors which compete more intensively with R&D for resources. We analyzed two ways in which technological change affects pollution. In the first, technological change increases the stock of knowledge and that makes it less costly for firms to control pollution. In the second, technological change augments productivity and hence reduces the need for polluting inputs.

Appendix I: The social planner's problem

Case (1): *Environmental quality is given by equation (7)*. In an optimal allocation all the quantities: $X_i(j)$, $X(j)$, and $L_x(j)$ will be the same for all $i = y, z$ and $j \in [0, M]$. This enables us to rewrite the social planner's problem as

$$\text{Max} \quad \int_0^\infty V(E, p_y, p_z, Q) e^{-\rho t} dt$$

s.t.

$$(2), (3), (6), (7), (26)$$

$$D_y + D_z = XM^{(1-\delta)\delta}$$

$$X = A_x K_x^\eta L_x^{1-\eta}$$

$$L = L_y + L_x + L_z + L_m$$

$$K = K_x + K_y + K_z + K_m$$

$$M(0) > 0 \text{ given.}$$

where L_x and K_x denote labor and capital used in all intermediate inputs sectors, respectively.

The current value Hamiltonian of this problem can be written as follows

$$\begin{aligned} H = & \frac{\left[\frac{EQ^\mu}{p_y p_z} \right]^{1-\sigma} - 1}{1-\sigma} + p_e(p_y Y + p_z Z - E) + p_Q(A_Q Y^{\epsilon_y} Z^{\epsilon_z} - Q) + r_y(A_y K_y^{\alpha_1} L_y^{\alpha_2} D_y^{\alpha_3} - Y) + \\ & r_x(A_x K_x^{\beta_1} L_x^{\beta_2} D_x^{\beta_3} - Z) + \bar{p}_d(XM^{(1-\delta)\delta} - D_y - D_z) + \bar{w}_L(L - L_y - L_z - L_x - L_m) + \\ & \bar{w}_k(K - K_y - K_z - K_x - K_m) + \lambda A_m K_m^\theta L_m^{1-\theta} M + \bar{p}_x(A_x K_x^\eta L_x^{1-\eta} - X), \end{aligned}$$

where p_e , r_y , r_z , \bar{p}_x , \bar{p}_d , \bar{w}_k , \bar{w}_L , and λ denote the shadow prices associated with the relevant constraints.

F.O.Cs are

$$\begin{aligned}
(1) \quad & \frac{\partial H}{\partial Y} = p_y p_y + \epsilon_y \frac{P_Q Q}{Y} - r_y = 0 \\
(2) \quad & \frac{\partial H}{\partial Z} = p_z p_z + \epsilon_z \frac{P_Q Q}{Z} - r_z = 0 \\
(3) \quad & \frac{\partial H}{\partial E} = E^{-\sigma} Q^{\mu(1-\sigma)} - p_e = 0 \\
(4) \quad & \frac{\partial H}{\partial Q} = \mu E^{1-\sigma} Q^{\mu(1-\sigma)-1} - p_Q = 0 \\
(5) \quad & \frac{\partial H}{\partial D_y} = \alpha_3 \frac{r_y Y}{D_y} - \bar{p}_d = 0 \\
(6) \quad & \frac{\partial H}{\partial D_z} = \beta_3 \frac{r_z Z}{D_z} - \bar{p}_d = 0 \\
(7) \quad & \frac{\partial H}{\partial K_y} = \alpha_1 \frac{r_y Y}{K_y} - \bar{w}_k = 0 \\
(8) \quad & \frac{\partial H}{\partial K_z} = \beta_1 \frac{r_z Z}{K_z} - \bar{w}_k = 0 \\
(9) \quad & \frac{\partial H}{\partial K_x} = \eta \frac{\bar{p}_x X}{K_x} - \bar{w}_k = 0 \\
(10) \quad & \frac{\partial H}{\partial K_m} = \theta \frac{\lambda \dot{M}}{K_m} - \bar{w}_k = 0 \\
(11) \quad & \frac{\partial H}{\partial L_y} = \alpha_2 \frac{r_y Y}{L_y} - \bar{w}_L = 0 \\
(12) \quad & \frac{\partial H}{\partial L_z} = \beta_2 \frac{r_z Z}{L_z} - \bar{w}_L = 0 \\
(13) \quad & \frac{\partial H}{\partial L_x} = (1-\eta) \frac{\bar{p}_x X}{L_x} - \bar{w}_L = 0 \\
(14) \quad & \frac{\partial H}{\partial L_m} = (1-\theta) \frac{\lambda \dot{M}}{L_m} - \bar{w}_L = 0 \\
(15) \quad & \frac{\partial H}{\partial X} = p_d M^{\frac{1-\delta}{\delta}} - \bar{p}_x = 0 \\
(16) \quad & \dot{\lambda} = \rho \lambda - \frac{(1-\delta) \bar{p}_d (D_y + D_z)}{\delta M} - \lambda \frac{\dot{M}}{M}.
\end{aligned} \tag{A.1}$$

We find it instructive to compare these optimality conditions to some of the competitive equilibrium conditions. If we substitute the demand for labor and capital from equations (A.1.5 - A.1.15) in the production function for Y, Z, X, and \dot{M} we arrive at the following

$$r_y = \bar{w}_k^{\alpha_1} \bar{w}_L^{\alpha_2} \bar{p}_d^{\alpha_3}, \quad r_z = \bar{w}_k^{\beta_1} \bar{w}_L^{\beta_2} \bar{p}_d^{\beta_3}, \quad \bar{p}_x = \bar{w}_k^{\eta} \bar{w}_L^{1-\eta}, \quad \bar{p}_d = \bar{p}_x M^{\frac{\delta-1}{\delta}}, \quad \lambda = \frac{\bar{w}_k^{\theta} \bar{w}_L^{1-\theta}}{A' M}. \tag{A.2}$$

Compare these to equations (8), (9), (10'), (11), and (13). We see here the social planner adjust prices

to account for externalities and noncompetitiveness. The noncompetitiveness is corrected for in the equation for p_x . Here the marginal cost of producing the X is equated to the shadow price of X. There is no mark-up over marginal cost as in the market solution. To see more clearly how pollution is corrected manipulate equations (A.1.1 - A.1.4) to get an identity that is valid if

$$r_y = [1+(\epsilon_y+\epsilon_z)\mu]p_y \text{ and } r_x = [1+(\epsilon_y+\epsilon_z)\mu]p_x \quad (\text{A.3})$$

So, foreign prices of Y and Z are adjusted for pollution externalities.

Let M grows at the constant rate g_m and both Y and Z grow at the rate \bar{g} (not necessarily constant). The above equations, with the fact that sectoral allocations for labor and capital are constant in all sectors and equations (A.1.3), (A.1.7), and (A.1.8) imply

$$(1-\Psi)\bar{g} = \frac{\dot{\bar{w}}_L}{\bar{w}_L} = \frac{\dot{\bar{w}}_K}{\bar{w}_K}, \quad (\text{A.4})$$

where $\Psi = \sigma + (1-\sigma)\mu(\epsilon+\eta)$ and \bar{g} is given by

$$\bar{g} = \frac{\alpha_3(1-\delta)}{\delta}g_m. \quad (\text{A.5})$$

Equations (A.2), (A.4), and (A.5) can be combined to obtain

$$\frac{\lambda}{\lambda} = \left[\frac{\alpha_3(1-\delta)(1-\Psi)}{\delta} - 1 \right] g_m. \quad (\text{A.6})$$

Using equations (A.1.5 - A.1.15) in the resource constraints and rearranging gives the national income as

$$r_y Y + r_z Z + \lambda M g_m = w_L L + w_K K. \quad (\text{A.7})$$

This result with equation (A.5) enables us to rewrite equation (A.1.16) as

$$\frac{\dot{\lambda}}{\lambda} = \rho - g_m - \frac{(1-\delta)\alpha_3}{\delta} A_m' \left(\frac{w_L}{w_K} \right)^\theta \left[L + \left(\frac{w_K}{w_L} \right) K \right] - g_m. \quad (\text{A.8})$$

From (A.3) and the cost functions in (A.2) we can obtain $(w_K/w_L) = (p_y/p_z)^{1/(\alpha_1-\beta_1)}$. Combing equations (A.6) and (A.8) and making use of this result we arrive at the growth rate of innovation in terms of the parameters of the model and exogenous variables as given by equation (32) in the text.

Case (2): Environmental quality is given by equation (7'). The current value Hamiltonian would be the same except for one modification: equation (7') requires $Q = A_q X^{-1} M^{(\epsilon-1)\epsilon}$. The equations that need to be changed in the F.O.Cs are

$$\begin{aligned} (1') \quad & \frac{\partial H}{\partial Y} = p_e p_y - r_y = 0 \\ (2') \quad & \frac{\partial H}{\partial Z} = p_e p_z - r_z = 0 \\ (15') \quad & \frac{\partial H}{\partial X} = p_d \frac{(D_y + D_z)}{X} - \frac{p_Q Q}{X} - p_x = 0 \\ (16') \quad & \dot{\lambda} = \rho \lambda - \frac{\epsilon-1}{\epsilon} \frac{p_Q Q}{M} - \frac{(1-\delta)}{\delta} p_d \frac{(D_y + D_z)}{M} - \frac{p_Q Q}{X} - \lambda \frac{\dot{M}}{M} \end{aligned} \quad (\text{A.1'})$$

The cost function will be given as before by the equations in (A.2) except for p_d . Using equations (A.1.1', 2'), (A.1.3-6), and (A.1.15') we get the following relation for p_d

$$\bar{p}_d = \frac{\alpha_3}{\alpha_3 - \mu} M^{\frac{\delta-1}{\delta}}. \quad (\text{A.10})$$

Since sectorial demands for labor and capital are constant in steady state X is also constant. This implies that Q grows at $(\epsilon-1)g_m/\epsilon$. Manipulating equations (A.1.1'), (A.1.2'), (A.1.3), (A.1.4),

differentiating the resulting expression with respect to time, and using the fact that E grows at $\alpha_3(1-\delta)g_m/\delta$ with the last result we obtain

$$\dot{p}_e = -\Psi' \frac{\alpha_3(1-\delta)}{\delta} g_m \quad (\text{A.10})$$

where $\Psi' = \sigma - \mu(1-\sigma)(\epsilon-1)\delta(1-\delta)\epsilon\alpha_3$.

equations (A.1.1') and (A.1.2') tells us that $r_y/r_z = p_y/p_z$. Using this with the cost functions gives $(w_k/w_L) = (p_y/p_z)^{1/(\alpha_1-\beta_1)}$. Hence, both w_k and w_L grow at the same rate which we can obtain by differentiating equation (A.1.7) with respect to time and observing that K_y is constant in the steady state. Thus,

$$\frac{\dot{\bar{w}}_L}{\bar{w}_L} = \frac{\dot{\bar{w}}_k}{\bar{w}_k} = (1-\Psi') \frac{\alpha_3(1-\delta)}{\delta} g_m, \quad (\text{A.11})$$

which with the cost function for R&D sector yields

$$\frac{\dot{\lambda}}{\lambda} = (1-\Psi') \frac{\alpha_3(1-\delta)}{\delta} - 1. \quad (\text{A.12})$$

Equation (A.1.15') can be manipulated as follows. $p_x X = -p_Q Q + p_d(D_y + D_z) = -p_Q Q + \alpha_3(r_y Y + r_z Z)$.

But from equations (A.1.1'), (A.1.2'), (A.1.3), and (A.1.4) we get $p_Q Q = \mu p_e E = \mu(r_y Y + r_z Z)$. Then

$p_x X = (\alpha_3 - \mu)(r_y Y + r_z Z)$. From the resource constraint we will be able to get: $w_k + w_L - \lambda M g_m =$

$p_x X + (1-\alpha_3)(r_y Y + r_z Z) = (1-\mu)(r_y Y + r_z Z)$. Using this result in equation (A.1.16') we get

$$\frac{\dot{\lambda}}{\lambda} = \rho - g_m - \Delta' \frac{(w_k K + w_L L)}{\lambda M} + \Delta' g_m, \quad (\text{A.13})$$

where $\Delta' = [(\epsilon-1)\epsilon + \alpha_3(1-\delta)/\delta]/(1-\mu)$. Equating (A.12) and (A.13) and rearranging we obtain the growth rate as in equations (32') in the text.

Appendix II: Tables and Figures

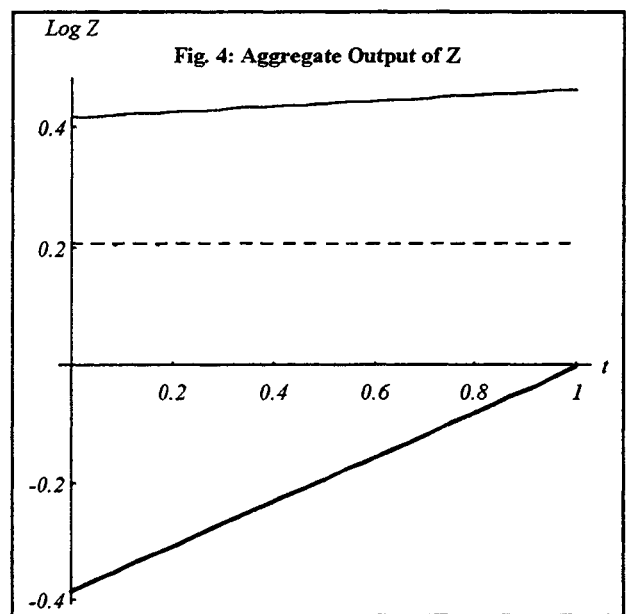
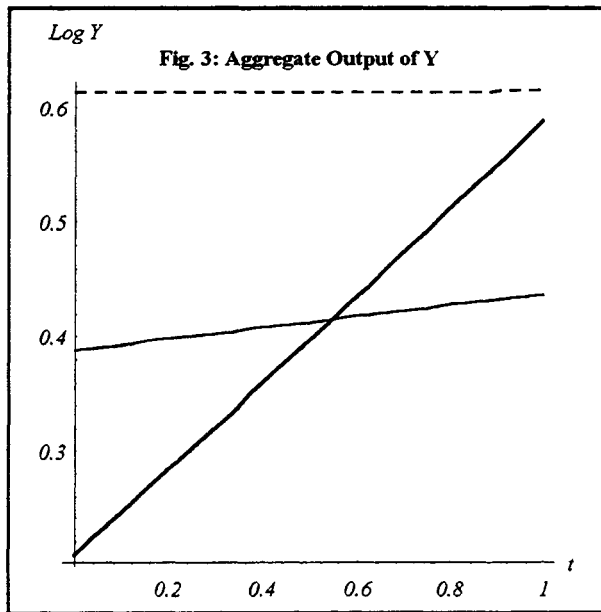
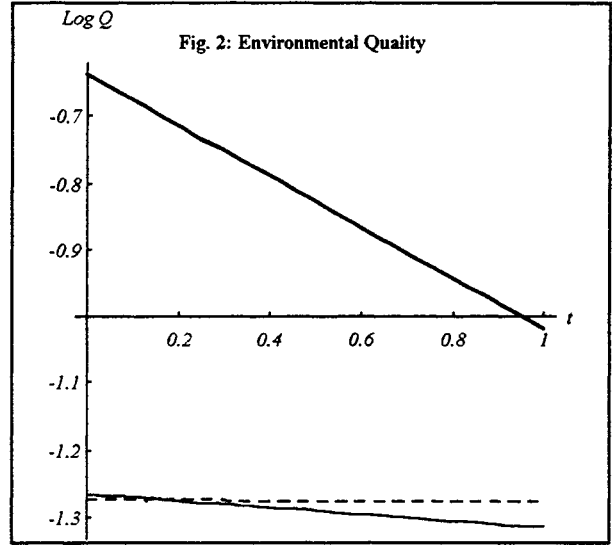
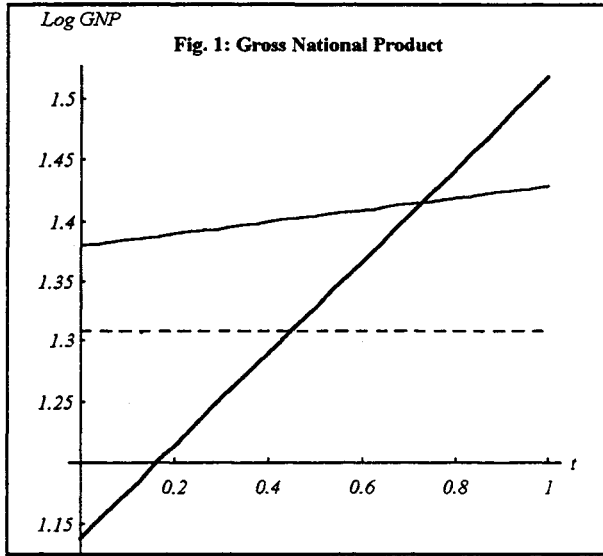
Table 1: Parameters.

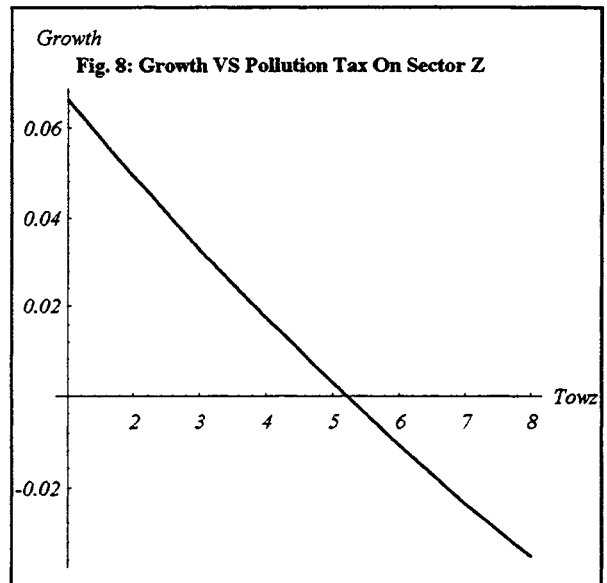
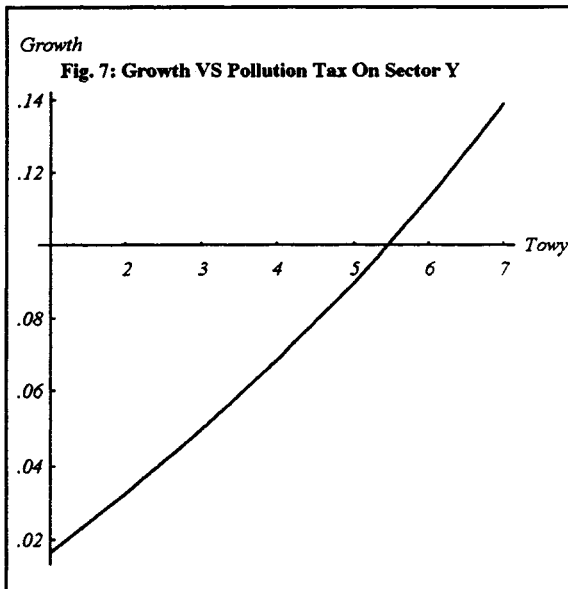
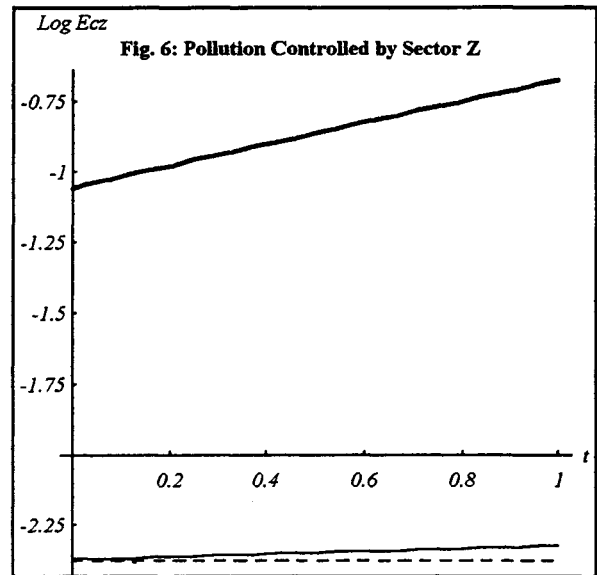
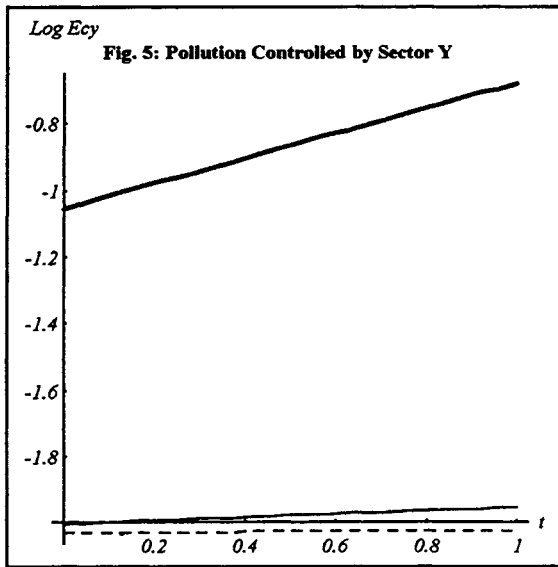
ϕ	μ	σ	ρ	ϵ_v	ϵ_z	A_o	α_1	α_2	α_3	A_v	β_1	β_2	β_3	A_z	δ	η
.5	.5	1.2	.47	-.5	-.5	1	.5	.25	.25	2.8	.25	.5	.25	2.8	.2	.1
A_v	A_{vz}	v_{1v}	v_{2v}	v_{1z}	v_{2z}	A_{cv}	A_{cz}	θ	A_m	p_v	p_z	τ_v	τ_z	A_x	K	L
2	3	.25	.1	.2	.15	1	1	.8	.25	1	1.6	.03	.02	1.3	4	1

Table 2: Steady State Values.

Variables ¹¹	Autarky Equilibrium	Trade Equilibrium	Pareto Optimal Equilibrium
Growth Rate ⁰	.00129	.0493	.3805
Output of Y ⁺	1.8467	1.4745	1.2303
Output of Z ⁺	1.2265	1.5168	.6809
Environmental Quality ⁻	.2797	.2823	.5282
GNP ⁺	3.6954	3.9734	3.1194
Emissions from Y ⁺	3.5618	2.8139	2.1131
Emissions from Z ⁺	3.5869	4.4571	1.6957
Emissions Controlled by Y ⁺	.1316	.135	.3475
Emissions Controlled by Z ⁺	.0926	.0932	.3471
Interest Rate ⁰	.4716	.5341	
Price of Capital ⁺	.2777	.2461	
Price of Labor ⁺	1.5522	1.7726	
Price of a New Design ⁰	1.566	1.4698	
Consumption of Y ⁺	1.8467	1.9507	1.1599
Consumption of Z ⁺	1.2265	1.2191	.7249
Welfare ⁰	-.4934	-.3171	-.0348

¹¹Variables with superscript 0 are constant over time, with + are growing at the common growth rate, and those with a minus superscript are growing at negative the growth rate.





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