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Bulletin Number 95-6

August 1995

ECONOMIC DEVELOPMENT CENTER

ENVIRONMENT IN THREE CLASSES OF ENDOGENOUS GROWTH MODELS

Elamin H. Elbasha and Terry L. Roe

ECONOMIC DEVELOPMENT CENTER
Department of Economics, Minneapolis
Department of Applied Economics, St. Paul

UNIVERSITY OF MINNESOTA

Environment in Three Classes of Endogenous Growth Models[1]

Elamin H. Elbasha Terry L. Roe
University of Minnesota

August 1995

Abstract

The implications of environmental externalities are studied within three classes of endogenous growth models viz. the linear technology models, the human capital models, and the R&D and innovation models. The long-run rate of economic growth changes when environmental externalities are introduced; the direction of change depends on the severity of externalities and the intertemporal elasticity of substitution. The presence of environmental externalities cause the decentralized growth rate to diverge from the efficient rate. Which rate is bigger than the other depends, among other things, on the valuation of consumption relative to environmental quality. Several policy changes to align the two paths are discussed. The models are calibrated to U.S. data.

I. Introduction

The new growth theory has produced models with many attractive features[2]. First, the engine of growth (be it accumulation of reproducible capital, industrial innovation, or research and development) is endogenous to the economy and possibly policy-sensitive. Second, learning-by-doing is an important source of technological change. Third, innovation is motivated by monopoly profits which are not completely appropriable because of the non-rival nature of

[1]Funding provided by USAID through the Environmental and Natural Resources Project.

[2]See the papers by Romer (1994), Grossman and Helpman (1994), and Solow (1994) in the Winter 1994 Symposia on New Growth Theory in the Journal of Economic Perspectives. For a textbook treatment see Barro and Sala-i-Martin (1995) and Grossman and Helpman (1991).

knowledge. Finally, imperfect competition specially in the innovation markets is modelled.

However, the new growth theory ignores altogether the interaction between growth and environment, even though there has been an increasing concern about the environment. The reason behind this concern is that environmental externalities have direct and indirect effects on individuals' welfare. The direct effects are related to the harm on human health and the damage to the amenity value of the environment. For instance, according to the estimates of the World Bank (1992), lack of access to clean water and sanitation are the major cause behind 900 millions cases of diarrheal diseases every year. About 1.3 billion people live in areas that did not meet World Health Organization's standard for particulate matter and 1 billion people inhabit areas that exceeded the standard for sulfur dioxide, hence facing the danger of serious respiratory disorders and cancers. Lead exposure accounts to 20% of the incidence of hypertension in Mexico City. Victims of indoor air pollution are estimated to be 400 millions. The depletion of the Ozone layer as a result of gases released from refrigerant poses also serious health threats. Loss of biodiversity is also occurring at alarming rates. During the eighties, tropical forests were deforested at an annual rate of 0.9%. Acid rains have also serious effects on the amenity value of the environment, killing trees and contaminating lakes.

The indirect effects are the reduced productivity effects of environmental degradation. The Greenhouse effect is important in this category. Global warming as a result of increasing emissions of CO_2 is expected to raise the sea level and disrupt agricultural production. Desertification resulting from cutting trees affects the productivity of agricultural land seriously. In some instances it results in a complete loss of agricultural land. (See, e.g., World Bank, 1992).

Several models of growth and environment have been proposed. However, they suffer from the following drawbacks. First, they ignore innovations and technological change, one of the most important engines of growth[3]. According to Grossman and Helpman (1994) "a story of

[3]There 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. The structure of our models and analysis are completely different from theirs. For a

growth that neglects technological progress is both ahistorical and implausible" (p. 26). Because they ignore innovations, the common result from these models is that optimal preservation of environmental quality and economic growth are competitive objectives. This result is in contradiction with what many economists believe (e.g., Lucas, 1994). They also tend to place emphasis on analyzing optimal growth only (even though markets do not behave optimally) rather than also considering a market driven dynamic equilibrium[4]. Work which has been done using market analysis concentrates on the cost of environmental policy and ignores externalities which are at the heart of environmental economics[5].

This paper is a first step toward integrating the theory of endogenous economic growth and environmental economics. It attempts to answer questions like the following. What difference dose it make to introduce environmental considerations in endogenous growth models? Do models with environment have different policy implications from those that exclude it? What are these policy implications? Is a competitive equilibrium Pareto optimal? Are there first-best policies? If first-best policies are not available, would there be second-best policies?

Endogenous growth models can be grouped into three main categories: convex models, human capital models, and innovation and R&D models. Convex models postulate convex preferences and production possibility set. Growth in these models is sustained because of a lower bound on the productivity of capital (e.g., Jones and Manuelli, 1990, and Rebelo, 1990). As their name suggests, human capital models sustain growth through accumulation of human capital (e.g., Lucas, 1988). The last category of models regard innovation and R&D activities (expanding varieties of goods or upgrading their quality) as a major source of economic growth (e.g., Romer,

model of trade, environment, and economic growth see Elbasha and Roe (1995).

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

[5]Examples are: Jorgenson and Wilcoxen (1990, 1993), 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 derived from a theoretical model.

1990, and Grossman and Helpman, 1991).

In this paper we take a representative model from each category and analyze the implications of incorporating environment in that model. We find that the presence of environmental concerns 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 from the ones that incorporate those effects. Whether larger or smaller depends on the intertemporal elasticity of substitution and the valuation of the environment relative to consumption. The standard comparative static results obtained from endogenous growth models without the environment remains valid only if the elasticity of intertemporal substitution is very high and/or consumption is valued more than the environment. If these conditions are not met, we arrive at the opposite results[6]. In the presence of environmental externalities, the decentralized growth rate can be larger or smaller than the efficient rate depending, inter alia, on whether the environment is valued more or less compared to consumption.

The paper is organized as follows. In Section II we introduce environment in the three models of endogenous growth. Agents in all these models get utility from consuming the only final good and enjoying the quality of the environment. Environment is polluted as a result of production activities taking place in the final output sector. In the first model there is only one factor of production and it can be accumulated as foregone consumption. In the second model human capital is the engine of growth. The final model is innovation-based and innovation is undertaken in the R&D sector which sells its blueprints to a monopolistic intermediate inputs sector. Growth takes place as a result of expansion in the varieties of intermediate inputs. In this section we discuss the "competitive" equilibrium and derive the determinants of sustained growth for all three models. The solution to a social planner's problem is also discussed and compared to the market equilibrium. We also derive the conditions under which the two solutions are different. Section III shows how a government can intervene to secure optimal allocations of resources.

[6]The comarative static results for the model without the environment are: growth rates varies positively with productivity and the elasticity of intertemporal substitution and negatively with the discount rate across steady states.

In Section IV we summarize our results and provide concluding remarks.

II. Endogenous growth models and the environment

In all the models we present below there are many identical infinitely-lived consumers. Population growth is taken to be zero. Preferences of a representative consumer are represented by the following instantaneous utility function[7]

$$U_t = \begin{cases} \frac{1}{1-\sigma}\left(\left[C(t)^{\phi}Q(t)^{\mu}\right]^{1-\sigma} - 1\right) & \text{for } \sigma \neq 1 \\ \phi \log C(t) + \mu \log Q(t) & \text{for } \sigma = 1, \end{cases} \tag{1}$$

where $C(t)$ denotes per capita consumption at time t, and $Q(t)$ stands for the quality of the environment. To satisfy monotonicity and strict concavity assumptions we impose the following restrictions: σ, ϕ, $\mu > 0$, $\phi(1-\sigma) < 1$, $\mu(1-\sigma) < 1$, $(\phi+\mu)(1-\sigma) < 1$.

There are two approaches for modeling changes in the quality of the environment: stock and flow. The first approach treats Q as a stock variable, the growth function of which changes negatively with economic activity, as approximated by aggregate output, and positively with the rate of natural decay. Examples of this are the quality of air and water. The second approach regards Q as a flow variable being affected negatively by aggregate economic activity. An extreme example of this is noise pollution. Since many of the endogenous growth models have two state variables, treating environmental quality as a stock variable will add another state variable to the model which extremely complicates the analysis. Our goal is simplicity. To that end, we regard environmental quality as a flow variable and assume the following relation

$$Q(t) = A_Q[Y(t)]^{-\eta},\ A_Q > 0,\ \eta > 0, \tag{2}$$

[7] This utility function exhibits the following properties (i) the elasticity of the marginal rate of substitution between consumption and environmental quality with respect to consumption, $\partial \log(U_Q\,/U_c)/\partial \log C$, is equal to one; (ii) the elasticity of the marginal utility of consumption is constant and equal to $1-\phi(1-\sigma)$; (iii) the elasticity of the marginal utility of environmental quality is constant and equal to $1-\mu(1-\sigma)$; and (iv) Inada conditions: $\lim_{C\to 0} U_c = \infty$, $\lim_{C\to\infty} U_c = 0$, $\lim_{Q\to 0} U_Q = \infty$, $\lim_{Q\to\infty} U_Q = 0$.

where $Y(t)$ is aggregate output at time t[8].

II.1 A Convex Endogenous Growth Model

We first consider environment in the simplest endogenous growth model (Rebelo, 1990). In this model there is only one factor of production: capital which is broadly defined. Production takes place according to the following constant returns to scale technology

$$Y(t) = AK(t),\ A > 0, \tag{3}$$

where $K(t)$ stands for capital at time t. We assume capital doesn't depreciate so we have the usual income identity

$$C(t) + \dot{K}(t) = Y(t). \tag{4}$$

The current value Hamiltonian for the social planner's problem is

$$H = \frac{1}{1-\sigma}[(C^{\phi}Q^{\mu})^{1-\sigma} - 1] + \lambda(AK - C),$$

where λ is the costate variable associated with the state variable K. The following conditions, together with the transversality conditions, are necessary and sufficient for an optimal solution

$$\frac{\partial H}{\partial C} = 0 \Rightarrow \phi C^{\phi(1-\sigma)-1} Q^{\mu(1-\sigma)} = \lambda \tag{5}$$

$$\dot{\lambda} = \rho\lambda - \frac{\partial H}{\partial K} \Rightarrow \dot{\lambda} = \rho\lambda + \mu\eta C^{\phi(1-\sigma)} Q^{\mu(1-\sigma)}/K - A\lambda, \tag{6}$$

where ρ denotes the discount rate.

We analyze only the steady state equilibrium in which $\dot{K}/K = \dot{C}/C = \dot{Y}/Y = g$ is a constant[9]. Using this fact and combining equations (2), (3), (4), (5), and (6) yields

$$g = \frac{A(1-\eta\mu/\phi) - \rho}{\Psi - \eta\mu/\phi}, \tag{7}$$

[8] Of course the flow approach is a special case of the stock approach.

[9] It can be shown that equilibrium in this model does not involve transitional dynamics. That is, the economy is always in a steady state.

where $\Psi = 1 - \phi(1-\sigma) + \mu\eta(1-\sigma)$. Note that the growth rate in equation (7) can be positive or negative. However, if we impose the assumption that investment is irreversible ($\dot{K} \geq 0$), then $g \geq 0$.

In the decentralized solution consumers treat Q as given as far as their consumption and capital accumulation decisions are concerned. Thus equation (6), in competitive equilibrium, becomes

$$\dot{\lambda} = \rho\lambda - A\lambda. \tag{8}$$

Following the same procedure as before we calculate the decentralized growth rate as

$$g_m = \frac{A-\rho}{\Psi}. \tag{9}$$

There is one technical difficulty we need to deal with concerning the growth formulas in equations (7) and (9), namely the utility function might not be finite in the steady state equilibrium. To avoid this problem we make the following restrictions: $(1-\Psi)g - \rho < 0$ and $(1-\Psi)g_m - \rho < 0$. If we use the formulas in equations (7) and (9) we can rewrite these restrictions as $[(1-\Psi)A - \rho]/[1-\phi(1-\sigma)] < 0$ and $[(1-\Psi)A - \rho]/\Psi < 0$, respectively. Since $1 - \phi(1-\sigma) > 0$ by our concavity assumptions, we have $(1-\Psi)A - \rho < 0$ which, using the second constraint, implies $\Psi > 0$. We would also want to have $C/K = A - g > 0$ which amounts to $[(1-\Psi)A - \rho]/\{(1-\mu\eta/\phi)[1-\phi(1-\sigma)]\} < 0$. This, with the restriction on the boundedness of the utility function, implies $\phi > \mu\eta$. We have proved the following proposition.

Proposition 1 *Equilibrium exists only if consumers value consumption more than environmental quality.*

The market growth rate in equation (9) has the following properties.

Proposition 2 *Growth is higher (i) the more productive is the economy (as measured by A); (ii) the lower is the rate of time preference (ρ); (iii) the greater the intertemporal elasticity of substitution between consumption at two points in time ($\xi_c = 1/[1-\phi(1-\sigma)]$); or (iv) the* *smaller is the intertemporal elasticity of substitution between environmental quality at two points in time* ($\xi_Q = 1/[1 - \mu(1-\sigma)]$ *).*

Proof. Differentiating equation (9) with respect to the relevant variable we obtain

$$
\begin{aligned}
\text{(i) } \frac{\partial g_m}{\partial A} &= \frac{1}{\Psi} > 0. \\
\text{(ii) } \frac{\partial g_m}{\partial \rho} &= -\frac{1}{\Psi} < 0. \\
\text{(iii) } \frac{\partial g_m}{\partial \xi_c} &= -\frac{g_m}{\Psi}\frac{\partial \Psi}{\partial \xi_c}. \text{ But } \frac{\partial \Psi}{\partial \xi_c} < 0 \text{ . So, } \frac{\partial g_m}{\partial \xi_c} > 0. \\
\text{(iv) } \frac{\partial g_m}{\partial \xi_Q} &= -\frac{g_m}{\Psi}\frac{\partial \Psi}{\partial \xi_Q}. \text{ But } \frac{\partial \Psi}{\partial \xi_Q} > 0. \text{ So, } \frac{\partial g_m}{\partial \xi_Q} < 0. \blacksquare
\end{aligned}
$$

Qualitatively some of these comparative statics results are the same as those obtained from the model without the environment. If we ignore environmental externalities, the denominator of equation (9) is replaced by the expression $1 - \phi(1-\sigma)$ which is also positive if the utility function is strictly concave. However, the quantitative effects of environmental externalities are important as the following proposition suggests.

Proposition 3 *Convex growth models that ignore the environment (i.e. $\mu\eta = 0$) produce growth rates which are greater, equal to, or smaller than those which incorporate the environment depending on whether the intertemporal elasticity of substitution is greater than, equal to, or smaller than one, respectively.*

Proof. Differentiating equation (9) with respect to μ yields

$$\frac{\partial g_m}{\partial \mu} = -\frac{g_m}{\Psi}\frac{\partial \Psi}{\partial \mu}. \text{ But } \frac{\partial \Psi}{\partial \mu} = \eta(1-\sigma). \text{ So, } \frac{\partial g_m}{\partial \mu} \gtreqless 0 \text{ as } \sigma \gtreqless 1. \text{ The latter requires } \xi_c \lesseqgtr 1. \blacksquare$$

Because there is a negative externality from output producers imposed on consumers which is not priced in the market equilibrium, one would expect the market growth rate to be larger than the Pareto optimal rate. This conjecture is true as the following proposition shows.

Proposition 4 *The competitive equilibrium growth rate is greater than the optimal rate.*

Proof. Let $\mu\eta \neq 0$. From equations (7) and (9) we have $g_m - g = -\mu\eta[A(1-\Psi) - \rho]/\phi\Psi(\Psi - \mu\eta/\phi)$. But in the optimal solution, the integral in the consumer's problem is finite if and only if $(1-\mu\eta/\phi)[A(1-\Psi)-\rho]/(\Psi - \mu\eta/\phi) < 0$. Thus $g_m - g > 0$ since $\phi > \mu\eta$ and Ψ is positive. Notice that if $\mu\eta = 0$, the two growth rates would be identical which is an intuitive result. ■

We now attempt to calibrate this model to U.S. data. From Cropper (1981) we can obtain an estimate for μ. Cropper (1981) regresses the logarithm of time spent ill on the logarithm of pollution (SO_2). He obtains a coefficient of 0.3. Hence, $\mu = 0.3$. The growth rate of SO_2 in the U.S. between 1940-1989 is .0032 per year (Statistical Abstract). Since the growth rate of output per capita is .014 (Lucas, 1988), we have $\eta = .0032/.014 = .2285$. Hall (1988) presents many estimates for the intertemporal elasticity of substitution. One of the estimates is obtained using Summers data. Even though it was obtained without consideration for the environment, we will use his estimate of .34 for the purposes of these exercises. In order to reduce the number of parameters to be estimated we set $\phi = 1$ so that the elasticity of substitution is measured by $1/\sigma$. Hence, $\sigma = 2.941$. This enables us to calculate Ψ as 2.808. Since the rate of interest, r, is .0675 (Lucas, 1988), the marginal productivity of capital, A, is equal to .0675. Because in equilibrium $\Psi g + \rho = r$, we have $\rho = .0281$.

With these estimates the market and efficient rates of growth are .014 and .0126, respectively. Hence, according to this model the U.S. economy is exceeding its rate of growth by 0.2%. It also suggests that environment is being degraded at a faster rate than what is optimally warranted (at a rate of .0032 compared to .0029).

II.2 Human Capital Models

We take the model of Lucas (1988, Sec. 4) as a representative of models in which the engine of growth is human capital accumulation. In this model there are two factors of production: physical and human capital. There are N identical workers, each endowed with one unit of time that has to be allocated between work, u, and human capital accumulation. The level of human capital of each worker is denoted by h. So, the effective workforce is uhN. Since population growth is zero, we normalize N to one and measure every variable in per capita terms. The production function has similar properties as that in equation (3), namely it exhibits constant returns to scale to all reproducible factors. In addition there are external effects of human capital, denoted by h_a. Thus,

$$Y(t) = AK(t)^{\beta}[u(t)h(t)]^{1-\beta}h_a(t)^{\gamma},\ 0 < \beta < 1,\ \gamma > 0. \tag{10}$$

Human capital is accumulated according to the following relation

$$\dot{h}(t) = \delta h(t)[1 - u(t)],\ \delta > 0. \tag{11}$$

The current value Hamiltonian for the social planner's problem is

$$H = \frac{1}{1-\sigma}[(C^{\phi}Q^{\mu})^{1-\sigma} - 1] + \theta_1[AK^{\beta}(uh)^{1-\beta}h^{\gamma} - C] + \theta_2\delta h(1-u),$$

where θ_1 and θ_2 denote the costate variables associated with physical and human capital, respectively. The following are necessary conditions for optimality

$$\frac{\partial H}{\partial C} = 0 \Rightarrow \phi C^{\phi(1-\sigma)-1}Q^{\mu(1-\sigma)} = \theta_1 \tag{12}$$

$$\frac{\partial H}{\partial u} = 0 \Rightarrow \theta_1(1-\beta)\frac{Y}{u}\left(1 - \frac{\mu\eta}{\phi}\frac{C}{Y}\right) = \theta_2\delta h \tag{13}$$

$$\dot{\theta}_1 = \rho\theta_1 - \frac{\partial H}{\partial K} \Rightarrow \dot{\theta}_1 = \rho\theta_1 - \theta_1\beta\frac{Y}{K}\left(1 - \frac{\mu\eta}{\phi}\frac{C}{Y}\right) \tag{14}$$

$$\dot{\theta}_2 = \rho\theta_2 - \frac{\partial H}{\partial h} \Rightarrow \dot{\theta}_2 = \rho\theta_2 - \theta_1(1-\beta+\gamma)\frac{Y}{h}\left(1 - \frac{\mu\eta}{\phi}\frac{C}{Y}\right) - \theta_2\delta(1-u). \tag{15}$$

It should be noted that in deriving conditions (13-15), we have made use of equations (2) and (12). Combining equations (13) and (15) we arrive at

$$\frac{\dot{\theta}_2}{\theta_2} = \rho - \delta - \frac{\gamma\delta}{1-\beta}u. \tag{16}$$

In what follows we concentrate on analyzing the properties of the steady state which we define as the state that satisfy all the above conditions and, in addition, all the variables grow at constant rates while u is constant. It is not difficult to show that capital, consumption, and output all grow at the same constant rate. Let us denote this rate by g and the rate at which human capital accumulates by ν. Thus from equations (10) and (11) we have $g = (1-\beta+\gamma)\nu/(1-\beta)$ and $\nu = \delta(1-u)$. Substituting equation (2) into equation (12) and differentiating the resulting equation with respect to time yields

$$\frac{\dot{\theta}_1}{\theta_1} = -\Psi g. \tag{17}$$

Differentiating equation (13) with respect to time and using equation (17) gives

$$\frac{\dot{\theta}_2}{\theta_2} = (1-\Psi)g - \nu. \tag{18}$$

Combing equations (11), (16), and (18) and rearranging we arrive at the optimal rate of human capital accumulation

$$\nu = \frac{1}{\Psi}\left(\delta - \rho\frac{1-\beta}{1-\beta+\gamma}\right). \tag{19}$$

In the market equilibrium equation (13) becomes

$$\frac{\partial H}{\partial u} = 0 \Rightarrow \theta_1(1-\beta)\frac{Y}{u} = \theta_2\delta h, \tag{20}$$

which if combined with equation (17) once again yields equation (18). However, equation (16) changes to

$$\frac{\dot{\theta}_2}{\theta_2} = \rho - \delta. \tag{21}$$

Combining equations (18) and (21) gives the market rate of human capital accumulation, ν_m, as

$$\nu_m = \frac{(\delta-\rho)(1-\beta)}{\Psi(1-\beta+\gamma)-\gamma}. \tag{22}$$

As before we want the growth formulas in equations (19) and (22) to satisfy the following restrictions: $\nu > 0$, $\nu_m > 0$, $(1-\Psi)(1-\beta+\gamma)\nu/(1-\beta) - \rho < 0$, $(1-\Psi)(1-\beta+\gamma)\nu_m/(1-\beta) - \rho < 0$. The last two restrictions require $\{(1-\Psi)(1-\beta+\gamma)\delta/(1-\beta) - \rho\}/\Psi < 0$ and $\{(1-\Psi)(1-\beta+\gamma)\delta/(1-\beta) - \rho\}/[\Psi(1-\beta+\gamma)-\gamma] < 0$. This implies $\Psi(1-\beta+\gamma)-\gamma$ has the same sign as Ψ.

Proposition 5 *if Ψ is greater (less) than zero, growth would be higher (i) the more (less) productive is the economy (as measured by δ); (ii) the lower (higher) is the rate of time preference (ρ);*

(iii) the greater (smaller) the intertemporal elasticity of substitution between consumption at two points in time ($\xi_c = 1/[1-\phi(1-\sigma)]$); or (iv) the smaller (greater) is the intertemporal elasticity of substitution between environmental quality at two points in time ($\xi_Q = 1/[1-\mu(1-\sigma)]$).

Proof. Differentiating equation (22) with respect to the relevant variable we obtain

$$\text{(i) } \frac{\partial \nu_m}{\partial \delta} = \frac{1-\beta}{\Psi(1-\beta+\gamma)-\gamma} \gtrless 0 \text{ as } \Psi \gtrless 0.$$

$$\text{(ii) } \frac{\partial \nu_m}{\partial \rho} = -\frac{1}{\Psi(1-\beta+\gamma)-\gamma} \gtrless 0 \text{ as } \Psi \gtrless 0.$$

$$\text{(iii) } \frac{\partial \nu_m}{\partial \xi_c} = -\frac{g_m}{\Psi(1-\beta+\gamma)-\gamma}\frac{\partial \Psi}{\partial \xi_c}. \text{ But } \frac{\partial \Psi}{\partial \xi_c} < 0. \text{ So, } \frac{\partial g_m}{\partial \xi_c} \gtrless 0 \text{ as } \Psi \gtrless 0.$$

$$\text{(iv) } \frac{\partial \nu_m}{\partial \xi_Q} = -\frac{g_m}{\Psi(1-\beta+\gamma)-\gamma}\frac{\partial \Psi}{\partial \xi_Q}. \text{ But } \frac{\partial \Psi}{\partial \xi_Q} > 0. \text{ So, } \frac{\partial g_m}{\partial \xi_Q} \gtrless 0 \text{ as } \Psi \lessgtr 0. \blacksquare$$

One can immediately notice how incorporating environmental externalities into this endogenous growth model changes the results. To see that remember in this model without the environment (i.e. when $\mu\eta = 0$), the denominator in equation (22) is equal to $[1-\phi(1-\sigma)][(1-\beta+\gamma)-\gamma]$ which is positive if the human capital externality, γ, is mild. In that case growth increases with A and ξ_c and decreases with ρ. However, in the case where environmental externalities are present, the denominator can be negative and in that circumstance these comparative static results are reversed. Notice that Ψ is negative only if $\sigma > 1$ and $\mu\eta > \phi$. That is, Ψ is negative when the elasticity of intertemporal substitution is low and agents value the environment more than consumption. The intuition behind the results reported in Proposition 5 is as follows. Suppose there is an exogenous increase in productivity. This has two opposing effects on welfare. On the one hand, as the economy becomes more productive consumers will be able to enjoy more consumption and increase investment in both physical and human capital because the rates of return are higher. On the other hand, environment is degraded as more consumption goods are produced. If consumption is valued more than the environment and/or the elasticity of substitution is high, consumers respond by increasing the rate at which they are consuming and investing. If however, the elasticity of substitution is low and consumers value consumption less than the environment, consumers invest and consume at a slower rate. The rest of the comparative statics results can be explained in a similar manner.

Proposition 6 *Growth is higher the less (more) consumers value consumption than environment as the elasticity of intertemporal substitution is less (greater) than one.*

Proof. Agents value consumption more than the environment if and only if $\phi > \mu\eta$. Let $\Psi = 1 + (\mu\eta - \phi)(1 - \sigma)$ be positive. Then Ψ is smaller and growth is higher if and only if ϕ is greater (smaller) than $\mu\eta$ and σ is smaller (greater) than one. The case where $\Psi < 0$ is consistent with the above result since $\Psi < 0$ only if $\sigma > 1$ and $\mu\eta > \phi$. ■

Whether the market produces excessive capital accumulation or not is not clear right away. There are two externalities in this model: a negative externality from pollution and a positive spill-over effects of human capital. The following proposition shows which externality is more dominant.

Proposition 7 *If there is no externality from human capital (i.e. $\gamma = 0$), the optimal growth rate and the market rate would be identical. If $\gamma > 0$, the market rate is always below the efficient rate provided $\Psi > 0$. If $\gamma > 0$ and $\Psi < 0$, the market rate is above the efficient rate.*

Proof. If $\gamma = 0$, then the right hand side of equations (19) and (22) are identical and so are the growth rates. For the case $\gamma > 0$ subtract equation (19) from equation (20) to get $\nu_m - \nu = \gamma(1 - \beta + \gamma)[\delta(1 - \Psi)(1 - \beta + \gamma)/(1 - \beta) - \rho]/(1 - \beta)\Psi[\Psi(1 - \beta + \gamma) - \gamma]$. But utility is bounded in the market solution only if $[\delta(1-\Psi)(1-\beta+\gamma)/(1-\beta)-\rho]/[\Psi(1-\beta+\gamma)-\gamma] < 0$. Therefore if $\Psi > 0$, then the market rate is always below the efficient rate. If $\Psi < 0$, the market rate is above the efficient rate. ■

Given a positive human capital externality, environmental externalities cause optimal rate to exceed the market growth rate if consumption is more valued than the environment and/or the elasticity of substitution is high. The market growth rate is higher than the optimal rate when the environment is more valued and the elasticity of substitution is low. However, unlike previous results, environmental externalities do not cause a divergence between the two rates if there is no human capital externality.

When calibrating his model to U.S. data, Lucas (1988) uses the following equilibrium values for some of the key variables: output growth 0.014, growth rate of human capital 0.009, and rate of return on capital of 0.0675. He obtains the following parameters estimates: $\beta = .25$ and $\gamma = 0.417$. He also gives an estimate for δ but since we don't allow population growth, we adjust his estimate to 0.0625. Using these parameters values with our earlier estimates of Ψ and ρ we calculate the efficient rates of growth for human capital and output as 0.0158 and 0.0246, respectively. The optimal effort need to be devoted to human capital accumulation is 0.2528. So, the U.S. economy ought to increase the effort devoted to human capital accumulation by 75% and enjoy growth in output about one percentage point more. If we ignore the environment, the implied value for ρ is 0.0265. Hence, the "efficient" rate of human capital accumulation is 0.0155, the rate of output growth is .0241, and the time devoted to education is 0.248. Therefore, the model without the environment understates the efficient rate of economic growth by 0.0005. Unlike the previous model, this model suggests that the U.S. economy hasn't reached the optimal rate of environmental degradation yet. The optimal rate of environmental degradation is .0056 in contrast to the actual rate of .0032.

II.3 R&D and Innovation Models

The model that will be presented here is more disaggregated than the previous models (See Grossman and Helpman, 1991, Chap. 5, and Romer, 1990, for models of this type). It consists of the following sectors:

(i) *Final output sector*. This sector consists of a large number of identical firms which produce the consumer good. There are three factors of production: capital, K, labor, L_y, and a set of intermediate inputs, D. The production technology is a Cobb-Douglas function of the form

$$Y(t) = A_y K^\alpha D^\beta L_y^{1-\alpha-\beta},\ A_y,\ \alpha,\ \beta > 0,\ \alpha + \beta < 0. \tag{23}$$

The index of differentiated intermediate goods, D, is given by

$$D = \left(\int_0^{M(t)} x(i)^{\delta} di \right)^{1/\delta}, \ 0 < \delta < 1, \tag{24}$$

where $M(t)$ denotes the measure of differentiate products available in the market at time t. Both the product space, $\{i : 0 \leq i \leq \infty\}$, and its subset, the set of brands available at time t, $[0,\ M(t)]$, are assumed to be continuous. In this model technological change is the engine of growth which occurs as a result of expansion in the variety of differentiated goods.

We will continue to assume that final output producers pollute the environment and the relation between economic activity and environmental quality is governed by equation (2).

(ii) *Intermediate inputs sector*. We assume that each brand $i \in [0, M]$ of differentiated inputs is produced by a single firm. Once it acquires the license to use the blueprints of brand i, firm i will become the sole producer of that brand. It uses only labor as a factor of production. It is assumed here that a unit of output of brand i, $x(i)$, is produced using only $1/A_x$ units of labor, $L_x(i)$. So,

$$x(i) = A_x L_x(i), \ A_x > 0. \tag{25}$$

(iii) *R&D sector*. We assume there exits a sector that undertakes research and development. This sector consists of a large number of firms. A representative firm in this sector uses labor, L_m, and knowledge (see below) to produce new blueprints and so add to the set of available brands. The technology for this product development is given by

$$\dot{M} = A_m L_m K_m, \ A_m > 0, \tag{26}$$

where K_m denotes the stock of knowledge which, for simplicity, we take to be equal to M. That is, $K_m = M$.

We will abandon our previous assumption that all markets are competitive and allow the market for differentiated inputs to be monopolistic. The rest of the sectors remain competitive.

The objective of a representative final output producer is to maximize profits taking the output price, input prices, and number of differentiated inputs as given. Formally,

$$\max_{Y,D,L_y,K,x(i)} Y - wL_y - rK - p_d D \quad s.t. \ (23), (24),$$

where w is wage rate, r is interest rate, and p_d denotes the price of D. Instead of solving the whole problem at once we will utilize the nature of the objective function and constraints and use some results from duality theory to decompose it into two smaller problems. The solution of these small problems will of course solve the original problem. It is helpful to think of the activities in the final output sector as being carried in two different departments: production and intermediate inputs assembly department.

The problem in the production department is to choose L_y, K, and D so as to minimize $wL_y + rK + p_d D$ subject to the production function in equation (23). This gives rise to the usual Cobb-Douglas cost function. Maximization of profits for this department is achieved by setting price equal to the unit cost[10]. That is,

$$1 = Br^{\alpha} p_d^{\beta} w^{1-\alpha-\beta}, \tag{27}$$

where $B^{-1} = A_y \alpha^{\alpha} \beta^{\beta} (1-\alpha-\beta)^{1-\alpha-\beta}$.

The demand functions for K, D, and L_y can be obtained using Shepherd's lemma by differentiating the cost function in equation (27) with respect to the relevant input price. Thus, $K = \alpha Y/r$, $D = \beta Y/p_d$, and $L_y = (1-\alpha-\beta)Y/w$.

In the intermediate inputs assembly department the demand for a differentiated input is obtained by solving the second problem which entails minimizing expenditure on differentiated products subject to the production function in equation (24). The cost function resulting from solving this problem is

$$\int_0^M p_x(i)x(i)di = D\left(\int_0^M p_x(j)^{\delta/(\delta-1)}dj\right)^{(\delta-1)/\delta} \tag{28}$$

[10]As we did earlier, we chose the final output's price as the numeraire.

where $p_x(i)$ denotes the price of brand i. The demand for a differentiated input $x(i)$ is obtained, through Shepherd's lemma, by differentiating the above function with respect to $p_x(i)$. Hence,

$$x(i) = p_x(i)^{1/(\delta-1)} D \left(\int_0^M p_x(j)^{\delta/(\delta-1)} dj \right)^{-1/\delta}, \ i \in [0, M]. \tag{29}$$

Profits maximization for this department requires equating the price index p_d to the unit cost, the latter is obtained by differentiating the right hand side of equation (28) with respect to D. Thus,

$$p_d = \left(\int_0^M p_x(j)^{\delta/(\delta-1)} dj \right)^{(\delta-1)/\delta}. \tag{30}$$

Each firm in the intermediate goods sector maximizes profit taking into account the demand function in equation (29). The level of profits of firm i is given by

$$\pi(i) = [p_x(i) - \frac{w}{A_x}]x(i), \ i \in [0, M], \tag{31}$$

where $\pi(i)$ denotes profits of firm i from producing brand i. Profits are maximized by charging a price such that

$$p_x(i) = \frac{w}{\delta A_x}, \ i \in [0, M]. \tag{32}$$

Therefore, in equilibrium p_x, x, and hence the level of profit π, are the same for all firms producing intermediate inputs. The common profit level is

$$\pi = (1 - \delta) p_x x. \tag{33}$$

Firms in the R&D sector choose $\dot{M}$ and L_m to maximize $p_m \dot{M}(t) - wL_m$ subject to equation (26) taking as given the price of a new design, p_m, and stock of knowledge, M. This gives rise to the following condition

$$p_m = \frac{w}{A_m M}. \tag{34}$$

Free entry in and exit from the R&D sector guarantees that the price of a new design at time t is equal to the cumulative present value of profits any firm in the intermediate goods sector earns. That is,

$$p_m(t) = \int_t^\infty e^{-\int_t^s r(n)dn} \pi(s) ds. \tag{35}$$

Differentiating equation (35) with respect to time and making use of that equation again yields the following no-arbitrage condition

$$\frac{\dot{p}_m(t)}{p_m(t)} + \frac{\pi(t)}{p_m\,(t)} = r\,(t)\,. \tag{36}$$

Equation (36) says the following: the rate of return from holding equities (i.e. dividends plus capital gains or losses) is equal to the rate of return on a consumption loan which is, in turn, equal to the rental rate of capital.

The consumer's problem can be written as

$$\max_{C(t)} \int_0^{\infty} U_t\, e^{-\rho t} dt$$
$$s.t.\;\; C\,(t) + \dot{a}\,(t) = w(t)L + r\,(t)\,a\,(t)\,,$$

where $a(t)$ denotes the total stock of assets (nonhuman wealth) held at time t and ρ is the discount rate. Application of the maximum principles yields the following condition

$$[\phi(1-\sigma)-1]\frac{\dot{C}\,(t)}{C\,(t)} + \mu(1-\sigma)\frac{\dot{Q}\,(t)}{Q\,(t)} = \rho - r(t). \tag{37}$$

In equilibrium, total usage of labor should be equal to total labor endowment. That is,

$$L_m(t) + L_y(t) + L_x(t) = L, \tag{38}$$

where L_x denotes total demand for labor by the intermediate inputs sector.

In order to calculate the equilibrium growth rate we proceed as follows. We obtain demand for labor in all sectors, make use of equations (36) and (38), and then eliminate interest rate by virtue of equation (37). Using the demand function for D, equations (33), and the accounting identity $Mp_x x = p_d D$, we can rewrite equation (36) as

$$\frac{\dot{p}_m}{p_m} + \frac{(1-\delta)\beta Y}{Mp_m} = r. \tag{39}$$

By solving for w from equation (34) and using the demand for labor in the final good sector we obtain $L_y = (1-\alpha-\beta)Y/A_m M p_m$. From equation (25) the demand for labor in all intermediate input sectors is $L_x = ML_x(i) = Mx/A_x$, and the identity $Mp_x x = p_d D$ gives $x = p_d D/Mp_x$. Hence, $L_x = p_d D/p_x A_x$. But from the demand function for D, equation (32) and (34) we have $p_d D/p_x A_x = \beta\delta Y/A_m M p_m$. The demand for labor in the intermediate goods sector is, therefore, given by $L_x = \beta\delta Y/A_m M p_m$. The Demand for labor in the R&D sector is obtained directly from equation (26), noting that $\dot{M}/M = g_m$ and $K_m = M$, as $L_m = g_m/A_m$. Substituting these sectorial labor demand functions into the resource constraint, equation (38), gives

$$g_m + [1 - \alpha - \beta(1-\delta)]\frac{Y}{Mp_m} = A_m L. \tag{40}$$

Solving for Y/Mp_m from the above equation and substituting it in equation (39) we arrive at

$$\frac{\dot{p}_m}{p_m} + \frac{(1-\delta)\beta}{1-\alpha-\beta(1-\delta)}(A_m L - g_m) = r. \tag{41}$$

As we did with earlier models, we will analyze only the steady state equilibrium; an equilibrium in which both M and p_m grow at constant (not necessarily the same) rates. If g_m is constant, then from equation (40), Y/Mp_m is also constant over time and Y grows at the same rate as Mp_m. Let us denote the growth rate of Y by g. Equation (34) implies w grows at rate g, which in turn using equation (32) suggests that $\dot{p}_x/p_x = g$. The constancy of Y/Mp_m, together with the demand functions for L_x and L_y, imply that all sectorial demands for labor are constant. Equation (39) and the fact that $\dot{p}_m/p_m$ being constant imply that the rate of interest is also constant. This together with the demand function for capital suggest a common growth rate for Y and K. Output and capital growing at the same rate implies, using the national income identity (equation (4)), the same growth rate for consumption. Differentiating equation (2) with respect to time and observing that Y grows at rate g, we arrive at the result that Q grows at rate $-\eta g$. Using this fact in equation (37) we obtain

$$\Psi g = r(t) - \rho, \tag{42}$$

where as before $\Psi = 1 - \phi(1-\sigma) + \mu\eta(1-\sigma)$. The fact that the total demand for labor in the intermediate inputs sector is constant implies that $\dot{x}/x = -g_m$. This suggests that D grows at rate $(1-\delta)g_m/\delta$. If we make use of this result in the production function given in equation (23), we arrive at

$$\frac{\dot{Y}}{Y} = g = \frac{\beta(1-\delta)}{\delta(1-\alpha)} g_m. \tag{43}$$

Equation (34) implies

$$\frac{\dot{p}_m}{p_m} = \frac{\dot{w}}{w} - \frac{\dot{M}}{M} = \left(\frac{\beta(1-\delta)}{\delta(1-\alpha)} - 1\right) g_m. \tag{44}$$

The growth rate, g_m, can easily be obtained now by combining equations (41), (42), (43), and (44) and rearranging. Thus,

$$g_m = \frac{\Delta A_m L - \rho}{\Delta + \frac{\beta(1-\delta)}{\delta(1-\alpha)}(\Psi - 1) + 1}, \tag{45}$$

where $\Delta = \beta(1-\delta)/[1-\alpha-\beta(1-\delta)]$. It should be noted that in this equilibrium the integral in the consumer's utility is always finite provided $\rho > (1-\Psi)g$. This is the same expression we encountered earlier.

As will be shown later, the sign of the denominator of equation (45) is the same as the sign of Ψ. Therefore, the relationship between productivity (A_m), rate of time preference (ρ), the elasticity of intertemporal substitution between consumption (ξ_c), and the elasticity of intertemporal substitution between environmental quality (ξ_Q) and the rate of economic growth is the same as that reported in Proposition 5. The results of Propositions 3 and 6 are also valid for this model. In addition we will have the following proposition.

Proposition 8 *The growth rate is higher the larger (smaller) is the endowment of labor (L) provided* $\Delta + \beta(1-\delta)(\Psi-1)/\delta(1-\alpha) + 1$ *is greater (smaller) than zero. If* $\Psi < 0$*, the growth rate decreases with the endowment of labor.*

Proof. To prove this proposition we only need to differentiate equation (45) with respect to L. Thus, $\partial g/L = A_m/[\Delta + \beta(1-\delta)(\Psi-1)/\delta(1-\alpha) + 1]$. This is positive or negative as $\Delta + \beta(1-\delta)(\Psi-1)/\delta(1-\alpha) + 1$ is positive or negative. We will show now that the latter term is positive (negative) if Ψ is (positive) negative. Suppose $\Psi > 0$. Then for the utility function to be bounded in the optimal solution we need to have $\beta(1-\delta)(\Psi-1)A_m L/\delta(1-\alpha) < \rho$ (see equation (46) below). But the labor resource constraint in the market solution requires labor employed in R&D be less than total labor endowment. That is, $[\beta(1-\delta)(\Psi-1)A_m L/\delta(1-\alpha) - \rho - A_m L]/[\Delta + \beta(1-\delta)(\Psi-1)/\delta(1-\alpha)+1] < 0$. These two inequalities imply $\Delta+\beta(1-\delta)(\Psi-1)/\delta(1-\alpha)+1 > 0$. Let us assume $\Psi < 0$. Then for the efficient rate to positive we need $\beta(1-\delta)A_m L/\delta(1-\alpha) < \rho$. Because $\Delta < \beta(1-\delta)/\delta(1-\alpha)$ we have $\Delta A_m L < \rho$. Thus for the market rate to be positive we need $\Delta + \beta(1-\delta)(\Psi-1)/\delta(1-\alpha)+1 < 0$. ■

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

$$\max_{C(t)} \int_0^\infty U_t e^{-\rho t} dt$$
$$s.t.\ (2), (4), (23), (24), (25), (26), (38).$$

The optimal growth rate of innovation is given by (see Appendix 1 for the derivation)

$$\tilde{g}_m = \frac{\frac{\beta(1-\delta)}{\delta(1-\alpha)} A_m L - \rho}{\frac{\beta(1-\delta)}{\delta(1-\alpha)}\Psi}. \tag{46}$$

If $\Psi > 0$, the optimal growth calculated in equation (46) has the following properties: growth is higher, the larger the labor endowment, the more productive is labor in the R&D sector, and the less patient the society becomes. If $\Psi < 0$, we obtain the opposite results, namely optimal growth varies negatively with endowment, productivity, and the degree of impatience.

Unlike the previous models, in this model there are three distortions: (a) imperfect competition in the market for intermediate inputs, (b) a positive externality in the R&D sector, and (c) a pollution externality from final output producers negatively affecting consumers. The distortion resulting from the noncompetitive pricing of intermediate inputs is a static one while the externality from knowledge spill-overs has a dynamic nature. The last distortion is the subject matter of this study.

Proposition 9 *If $\beta(1-\delta)/\delta(1-\alpha) = 1$, the steady state equilibrium is of the balanced growth type in which Y, K, C, and M grow at the same rate while p_m is constant.*

Proof. Use this condition in equations (43) and (44) the result will follow. ■

Proposition 10 *Let* $\Gamma = 1+\Delta- \beta(1-\delta)/\delta(1-\alpha)$. *In the absence of any government intervention, the decentralized competitive equilibrium growth path is always below the Pareto optimal one provided* $\Gamma \geq 0$ *and* $\Psi > 0$. *If* $\Gamma \geq 0$ *and* $\Psi < 0$, *the market rate is greater than the efficient rate.*

Proof. Let $\Psi > 0$. We will first show that the numerator in equation (45) is always smaller than that in equation (46). A sufficient condition for this to be true is $\Delta < \beta(1-\delta)/\delta(1-\alpha)$. Suppose this condition is not satisfied. Instead we will have $\Delta \geq \beta(1-\delta)/\delta(1-\alpha)$. After rearranging and canceling some terms, we will arrive at the condition $\alpha+\beta \geq 1$, an obvious contradiction to our restrictions on the parameters α and β. Second, the denominator in equation (45) is always bigger than that in equation (46) provided $\Gamma \geq 0$. Since equation (43) has a smaller numerator and a bigger denominator than equation (46), it follows that $g_m < \tilde{g}_m$. If $\Psi < 0$, $A_m L\beta(1-\delta)/\delta(1-\alpha)$ has to be less than ρ for the efficient rate to be positive. This in turn implies $A_m \Delta L < \rho$ (because $\Delta < \beta(1-\delta)/\delta(1-\alpha)$) and hence $1+\Delta+(1-\Psi)\beta(1-\delta)/\delta(1-\alpha) < 0$ for the market rate to be positive. Then by the previous reasoning equation (45) has a larger (in absolute value) numerator and a smaller denominator than equation (46). Hence, it follows that $g_m > \tilde{g}_m$. ■

The result that $g_m < \tilde{g}_m$ is interesting because its policy implications call for win-win policies (policies that boost growth while the environment can tolerate their effects). This also proves that growth and the environment are not necessarily substitutes. Optimal preservation of environmental quality calls for more economic growth than the market provides. Notice that $\Gamma \geq 0$ is a restriction on the parameters of technology. It does not involve any parameter from the utility function. It should be noted that a sufficient condition for $\Gamma \geq 0$ is $\beta(1-\delta)/\delta(1-\alpha) \leq 1$ which in turn implies that the rate at which innovation grows is always as high as that of output.

The above restrictions on Γ and Ψ are only sufficient conditions for the above results to be valid. The following proposition states the remaining cases.

Proposition 11 *Suppose* $\Psi < 0$ *and* $\Gamma < 0$. *The decentralized growth rate* (g_m) $\lesseqqgtr$ *Pareto* *optimal rate ($\tilde{g}_m$) if and only if* $\Gamma\rho/A_mL \lesseqqgtr [(1-\Psi)\Gamma+\Psi]\beta(1-\delta)/\delta(1-\alpha)$. *If* $\Psi > 0$ *and* $\Gamma < 0$*, there are two cases: (i)* $\Gamma + \Psi\beta(1-\delta)/\delta(1-\alpha) > 0$ *implies* $g_m \lesseqqgtr \tilde{g}_m$ *as* $\Gamma\rho/A_mL \lesseqqgtr [(1-\Psi)\Gamma+\Psi]\beta(1-\delta)/\delta(1-\alpha)$ *and (ii)* $\Gamma + \Psi\beta(1-\delta)/\delta(1-\alpha) < 0$ *implies* $g_m \lesseqqgtr \tilde{g}_m$ *as* $\Gamma\rho/A_mL \gtreqqless [(1-\Psi)\Gamma+\Psi]\beta(1-\delta)/\delta(1-\alpha)$.

We now calibrate this model to U.S. data. In order to reduce the number of parameters to be calibrated we set $\delta = \beta$ (this is a version of the model discussed in Romer, 1990). We use patents as a measure of the number of new designs. In the steady state we know that the growth of $\dot{M}$ is equal to g_m. Since the growth of patents issued in the U.S. between 1956-1990 is 0.025 per year, we have $g_m = 0.025$. Our previous estimate for β is 0.25 and g is .014. The value of δ implied by equation (43) is 0.58. Using this with the fact that $\Psi g + \rho = 0.0675$, in equation (45) implies $A_mL = .1882$. We normalize L to one so that $A_m = .1882$. With these estimates the economy is employing 13.3% of its labor force in the R&D sector, 10.8% in the intermediate inputs sector, and 75.9% in the final output sector. The following are the optimal values for some key variables: innovation rate is 0.067, rate of growth of output is 0.0375, employment in R&D is 35.6%, employment in intermediate inputs is 49.8%, and employment in the final output sector is only 14.6% of the total labor force. This suggests that the U.S. economy ought to devote more labor resources to the R&D sector (from 13.3% to 35.6%) and intermediate inputs sectors (from 10.8% to 49.8%). The economy also ought to innovate at a higher rate (about four percentage points more than it is doing now) and enjoy a rate of economic growth of nearly two and a half percent more. The efficient rate of environmental degradation is .0085 compared to the actual rate of .0032.

III. Policy implications

The divergence of the decentralized equilibrium growth path from the Pareto optimal one calls for government intervention. This section focuses on finding some "desirable" policy instruments. We look for first-best policies. First-best policies are by definition designed to remove all distortions.

In the convex model of endogenous growth, a pollution tax (or an income tax) is needed because market growth is bigger than the efficient growth rate. To see that, suppose the government implements a tax, τ, on income received. The tax-ridden growth formula will become $[A(1-\tau)-\rho]/\Psi$. Let the pre-policy market rate be g_m. Then this formula can be written as $g_m - \tau A/\Psi$. If we equate this to the efficient rate, g, we will get $\tau = (g_m - g)\Psi/A$. Because both A and Ψ are positive and $g_m > g$ the tax rate is indeed positive. With the parameters estimates reported in subsection II.1, the optimal tax rate is 5.8%.

The adjustment pressures that take the system instantaneously from the initial steady state to the new one can be described as follows. At the initial consumption, the income tax disturbs the household equilibrium. Households respond by reducing their savings. Because the interest is equal the always constant marginal productivity of capital, investment has to fall in order to maintain capital market equilibrium. The fall in investment causes the rate of economic growth and the rate at which the environment is degraded to decline.

In the model of human capital we need two policy instruments to achieve optimal allocations of resources: a pollution tax and a subsidy to investment in human capital. Because it is difficult to derive analytical formulas for these two policies we will not discuss them any further.

In the innovation-based model we need three policies for optimal allocation of resources: 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 allocation of the previous section can be decentralized into a competitive market driven equilibrium.

Instead of analyzing first-best policies we concentrate only on second-best policies. There are two reasons for this choice. First, in reality not all these instruments 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 a second-best world. Second, the chosen second-best instruments will produce the optimal growth rate. Unlike the previous models there a large degree of freedom in choosing among policies that influence growth. Here are the few which we have chosen.

(1) *A subsidy to R&D.* To encourage growth, suppose the government decided to pay a subsidy, χ_m, per unit of labor employed in the R&D sector every period. The subsidy is financed through a lump-sum tax collected from consumers. The effects of this policy change will be as follows[11]. The profit maximization condition in the R&D sector will be $A_m p_m M/(1-\chi_m) = w$. Following the same procedure in calculating the growth rate as before, we arrive at the following subsidy-ridden growth formula

$$g(\chi_m) = \frac{\beta A_m L/(1-\alpha)(1-\chi_m) - p}{\Psi + \beta/(1-\alpha)(1-\chi_m)}. \tag{47}$$

It is obvious that the growth rate is higher the bigger the size of the subsidy. To foster the competitive equilibrium growth so as to catch up with the optimal growth rate, the government has to choose the optimal size for the subsidy. It isn't hard to calculate that optimal size. Equating the growth rate in equation (47) with the optimal one in equation (46) and solving for χ_m yields

$$\chi_m^* = 1 - \frac{\beta}{1-\alpha}\left(1 - \frac{\tilde{g}_m}{A_m L}\right). \tag{48}$$

It is obvious that $0 < \chi_m^* < 1$. The optimal subsidy is an increasing function of L and A_m and a decreasing function of ρ. This implies that countries with large labor endowments, with more productive labor in R&D, and/or with more patient consumers should subsidize R&D more than other countries. When the model is calibrated, the optimal subsidy rate is 50.2%.

Let us now try to understand the mechanism through which this subsidy achieves the goal for which it is designed i.e. enhancing growth. To make the analysis simple, let us concentrate on what happens in period zero. The immediate and direct effect of the subsidy is to increase the demand for labor in the R&D sector. This will in turn have two effects. First, it raises the growth rate of M. Second, it causes an excess demand in the labor market. For the labor market to clear, the initial wage rate has to rise leading to a decrease in the demand for labor

[11] We analyze only the case where all variables grow at the same rate. This requires $\beta(1-\delta)/[\delta(1-\alpha)] = 1$.

in the final output and intermediate inputs sectors. The fall in L_y and L_x helps mitigate the demand pressure on labor and hence stops the wage rate from rising too much. Eventually, the decrease in both L_y and L_x will be equivalent to the increase in L_m. The effects of the subsidy on the profitability of producing intermediate inputs, through the wage rate, are obvious. While the rise in w causes a direct fall π in and an indirect decline in x, its indirect effects on p_x are more strong. The rise in p_x is high enough to compensate for the decline in profitability caused by the rise of labor costs and loss of production. The rate of return on equities issued by this sector, π/p_m, goes up. To maintain the asset market equilibrium, the rate of return on capital has to go up too. This in turn encourages more accumulation of capital. Hence the growth of capital is higher than before. This together with the previous result that M grows at a higher rate implies that final output also grows at a rate higher than before. Consumers anticipating all these changes in addition to the higher rate at which the quality of the environment deteriorates, respond by increasing the rate at which they consume. Hence growth in consumption is also higher than before the imposition of the subsidy. If we replicate this argument each period we will establish the result that growth has to be higher in each period. It should be noted that the main channel through which the subsidy boosts growth is by shifting labor resources away from other sectors of the economy and directing them into the production of new designs and knowledge capital.

(2) *A tax on labor in the final output sector.* The previous analysis tells us that the reason behind the success of a subsidy to R&D is its ability to divert labor resources from the final output and intermediate input sectors and direct them to R&D. This suggests that a policy to discourage employment in these two sectors might also work. Suppose the government imposes a tax, χ_y, on any unit of labor employed in the final output sector. As a result of this policy change the growth rate will be given by $g(\chi_y) = (\Delta' A_m L - \rho)/(\Delta + \Psi)$, where $\Delta' = (1-\alpha)\beta/\{(1-\alpha+\beta)[(1-\alpha-\beta)/(1+\chi_y) + \beta^2/(1-\alpha+\beta)]\}$. It is clear that the growth rate is an increasing function of the tax rate. Equating the tax-ridden growth rate with

the optimal one we obtain the following formula for the Pigouvian tax

$$\chi_y^* = \frac{(1-\alpha-\beta)(1-\alpha+\beta)A_m L}{\beta(1-\alpha)(A_m L-\tilde{g}) - A_m\beta^2 L} - 1 \tag{49}$$

(3) *A tax on labor in the intermediate inputs.* Like the previous one, this tax will have a direct effect on the labor employment in the sector from which it is collected. To align the two growth paths the government has to charge the following tax

$$\chi_d^* = \frac{A_m\beta^2 L}{(1-\alpha)(A_m L-\tilde{g}) - (1-\alpha-\beta)(1-\alpha+\beta)A_m L} - 1 \tag{50}$$

The reason behind the success of this tax in boosting growth is its ability to divert resources from intermediate inputs production and direct them into R&D.

(4) *An excise subsidy to the intermediate inputs sector.* Let us consider the effects of a subsidy, χ_x, given to the intermediate inputs sector per unit of each x produced. This subsidy is given to all firms in this sector in every period. As a result of the subsidy, each firm in this sector reacts by charging the price $p_x = w/\delta A_x(1+\chi_x)$ with its profits changing to $\pi = (1-\alpha)(1+\chi_x)p_x x/(1-\alpha+\beta)$. The no-arbitrage condition becomes $\rho + g = (1-\alpha)(1+\chi_x)Y/(1-\alpha+\beta)Mp_m$. Labor employment in the subsidy-affected sector will change to $L_x = \beta^2(1+\chi_x)Y/(1-\alpha-\beta)A_m M p_m$. The growth rate will be given by the formula $g(\chi_x) = (\bar{\Delta}A_m L-\rho)/(\bar{\Delta}+\Psi)$, where $\bar{\Delta} = (1-\alpha)\beta/\{(1-\alpha+\beta)[(1-\alpha-\beta)/(1+\chi_y)+\beta^2/(1-\alpha+\beta)]\}$. It is clear that the growth rate is an increasing function of the subsidy. It is interesting to note that the above growth formula is exactly the same as the one given earlier in the derivation of equation (49) if we replace χ_x by χ_y. This has the following implications. To achieve the optimal growth rate, instead of imposing the tax on labor employed in the final output sector, we can apply the identical subsidy to the output of intermediate inputs sector as given by the formula in equation (49).

This subsidy works because it increases the profitability of the intermediate inputs sector which in turn forces the price of new design to go up. As p_m rises, the growth rate of M also rises.

(5) *A subsidy to the profits of the intermediate inputs sector.* Suppose the government decided to motivate the intermediate inputs production by paying each firm in this sector a percentage, χ_π, of their profits each period as a subsidy. Even though they will continue to charge their prices according to the old formula, firms in this sector will earn a total profit of the magnitude $\pi = (1+\chi_\pi)(1-\delta)p_x x/(1-\alpha+\beta)$. As result the no-arbitrage condition becomes $(1+\chi_\pi)\beta(1-\alpha)Y/(1-\alpha+\beta)Mp_m$. This implies that the growth rate will be $g(\chi_\pi) = (\hat{\Delta}A_m L-\rho)/(\hat{\Delta}+\Psi)$, where $\hat{\Delta} = \beta(1+\chi_\pi)/(1-\alpha)$. The optimal subsidy rate is, therefore, given by

$$\chi_\pi^* = \frac{(1-\alpha)A_m L}{\beta(A_m L - \tilde{g})} - 1 \tag{51}$$

Notice that $\chi_\pi^* = \chi_m^*/(1-\chi_m^*)$. This subsidy has a direct effect on the profitability of the intermediate inputs sector.

(6) *Environmental policy.* Let the government levies an effluent, τ_p, charge per each unit of pollution emitted. This policy change will not have a "growth" effect. Instead it will only affects the level of the variables. With appropriate choice of level of τ_p, the pollution externality will be internalized and the distortion resulting from the noncompetitive pricing of intermediate inputs may be removed. This, however, will not affect the dynamic externality resulting from knowledge creation. Therefore, this policy alone will not be sufficient to align the competitive and optimal paths.

IV. Summary and Concluding Remarks

We have studied the welfare implications of environmental externalities in three classes of endogenous growth models. We started with analyzing the implication of the environment within the simplest endogenous growth model: the "AK" model. Incorporating environmental externalities into this model changes the rate of economic growth provided the elasticity of intertemporal substitution $(1/\sigma)$ is different from one. With low elasticity of intertemporal substitution and mild effects of environmental externalities on consumers' welfare, growth rate is higher than when the environment is ignored. The case where the elasticity of intertemporal substitution is small also implies the growth rate is higher when consumers value environment more than consumption than if they don't.

In the absence of environmental externalities (and other distortions) the First Theorem of Welfare Economics applies: market rate of growth and efficient rate are always the same. The presence of environmental externalities causes the market rate to diverge from the efficient rate. The market rate is always bigger than the efficient rate.

These results do not extend to the human capital models. The divergence between the two rates disappears if there is no human capital externality even when environmental externalities are present. Given there is a positive human capital externality and low elasticity of substitution, environmental externalities cause the market to over grow compared to what is optimal if consumption is more valued than the environment and to under grow if environment is valued more than consumption.

In the R&D and innovation model, environmental externalities add a third type of distortion and hence render the relationship between market and efficient rate of economic growth and the sources of distortions more complicated. With mild environmental externalities, high elasticity of intertemporal substitution, and/or low degree of monopoly power, the market rate is below the efficient rate. If, however, environmental externalities are strong and the elasticity of substitution is low and monopoly power is weak, the market rate will be high compared to what is optimal. When the degree of monopoly power is strong there are many possible cases and the relationship between the two growth rates could go either way.

The comparative static results are similar in the three models. If the elasticity of substitution is high and/or environmental externalities are mild (or agents valuation of consumption is more than the environment), we obtain standard comparative static results: growth increases with productivity and elasticity of intertemporal substitution and decreases with the discount rate. If not, we obtain the opposite results.

Due to the presence of distortion there is a lot of room for intervention. In the simple endogenous growth model there is a single type of distortion, namely environmental externalities.

In this case there is a need for only one first-best policy: an income tax. In the human capital model two policy instruments are needed: a pollution tax and subsidy to investment in human capital. To achieve optimal allocation of resources in the R&D and innovation model three instruments are needed: a pollution tax, a subsidy to correct the monopoly distortion, and a subsidy to R&D to pay for the positive externality of knowledge creation. If the interest is in growth, we have shown that only one policy instrument is needed. We discussed five of these instruments.

In both the human capital and R&D and innovation models the relationship between the market rate and the efficient rate is ambiguous. This suggests miscalculations may not only suggest wrong levels of policy instruments, it may even suggest wrong type of policy instruments. The need for empirical analysis is, therefore, imperative. The calibrated versions of these models put the optimal rate of economic growth above the market rate.

Appendix: Social planner's problem for the innovation model

Since the index function D treats all $x(i)$ the same, in an optimal solution labor will be allocated in equal amounts to the production of every $x(i)$. We will, therefore, have $D = A_x L_x M^{(1-\delta)/\delta}$ and $Y = A_y A_x^\beta K^\alpha L_x^\beta L_y^{1-\alpha-\beta} M^{(1-\delta)/\delta}$, where L_x denotes labor employment in all intermediate inputs sector. After some substitution we can write the current value Hamiltonian of this problem as

$$H = \frac{1}{1-\sigma}[(C^\phi Q^\mu)^{1-\sigma} - 1] + \gamma_1(Y - C) + \gamma_2(L - L_y - L_x)A_m M,$$

where γ_1 and γ_2 are the current value costate variables associated with the state variables K and M, respectively. First-order conditions are

$$\frac{\partial H}{\partial C} = 0 \Rightarrow \phi C^{\phi(1-\sigma)-1} Q^{\mu(1-\sigma)} = \gamma_1 \tag{A.1}$$

$$\frac{\partial H}{\partial L_x} = 0 \Rightarrow L_x = \beta \frac{\gamma_1 Y}{\gamma_2 A_m M}\left(1 - \frac{\mu\eta}{\phi}\frac{C}{Y}\right) \tag{A.2}$$

$$\frac{\partial H}{\partial L_y} = 0 \Rightarrow L_y = (1-\alpha-\beta)\frac{\gamma_1 Y}{\gamma_2 A_m M}\left(1 - \frac{\mu\eta}{\phi}\frac{C}{Y}\right) \tag{A.3}$$

$$\dot{\gamma}_1 = \rho\gamma_1 - \alpha\frac{\gamma_1 Y}{K}\left(1 - \frac{\mu\eta}{\phi}\frac{C}{Y}\right) \tag{A.4}$$

$$\dot{\gamma}_2 = \rho\gamma_2 - \frac{\beta(1-\delta)}{\delta}\frac{\gamma_1 Y}{M}\left(1 - \frac{\mu\eta}{\phi}\frac{C}{Y}\right) - \gamma_2 A_m L_m. \tag{A.5}$$

Differentiating equation (A.1) with respect to time and rearranging gives

$$[\phi(1-\sigma) - 1]\frac{\dot{C}}{C} + \mu(1-\sigma)\frac{\dot{Q}}{Q} = \frac{\dot{\gamma}_1}{\gamma_1} \tag{A.6}$$

Using equation (A.2) we can rewrite equations (A.4) and (A.5) as

$$\frac{\dot{\gamma}_1}{\gamma_1} = \rho - \alpha\frac{Y}{K}\left(1 - \frac{\mu\eta}{\phi}\frac{C}{Y}\right) \tag{A.7}$$

$$\frac{\dot{\gamma}_2}{\gamma_2} = \rho - \frac{\beta(1-\delta)}{\delta}\frac{Y}{M}\left(1 - \frac{\mu\eta}{\phi}\frac{C}{Y}\right)\frac{\gamma_1}{\gamma_2} - A_m L_m. \tag{A.8}$$

As mentioned earlier, our interest here is in an equilibrium with the following properties. The rate of innovation, $\tilde{g}_m$, is constant while $\dot{C}/C = \dot{K}/K = \dot{Y}/Y = -1/\eta * \dot{Q}/Q) = \tilde{g}$. Then from the production function for final output we have

$$\tilde{g} = \frac{\beta(1-\delta)}{\delta(1-\alpha)}\tilde{g}_m. \tag{A.9}$$

From equation (A.6) we have

$$\frac{\dot{\gamma}_1}{\gamma_1} = -\Psi\tilde{g}. \tag{A.10}$$

Substituting equations (A.2) and (A.3) in the labor constraint gives

$$\frac{Y}{A_m M}\left(1 - \frac{\mu\eta}{\phi}\frac{C}{Y}\right)\frac{\gamma_1}{\gamma_2} = \frac{L - L_m}{1-\alpha}. \tag{A.11}$$

Using this in equation (A.8) yields

$$\frac{\dot{\gamma}_2}{\gamma_2} = \rho - \frac{\beta(1-\delta)}{\delta(1-\alpha)}A_m L + \left[\frac{\beta(1-\delta)}{\delta(1-\alpha)} - 1\right]\tilde{g}_m \tag{A.12}$$

If the rate of growth of innovation is constant, then equation (A.12) implies that $\dot{\gamma}_2/\gamma_2$ is also constant. Hence equations (A.8), (A.9), and (A.10) suggest

$$\frac{\dot{\gamma}_2}{\gamma_2} = \frac{\dot{Y}}{Y} - \frac{\dot{M}}{M} + \frac{\dot{\gamma}_1}{\gamma_1} = \left[\frac{\beta(1-\delta)(1-\Psi)}{\delta(1-\alpha)} - 1\right]\tilde{g}_m \tag{A.13}$$

Substituting this result in equation (A.10) and rearranging we arrive at equation (46) in the text.

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