ENVIRONMENTAL QUALITY AND ECONOMIC DEVELOPMENT

BY

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Abstract

This dissertation contributes to the construction of a theoretical framework for understanding the relationship between environmental quality and economic development. In pursue of this goal, I specialize to dynamic growth models in which pollution is treated as an externality generated in the production sector and affecting the consumption sector. I consider the transitional dynamics and the steady state of not only the typical nations that start their development with a small stock of capital and a large stock of the environment, but also an important group of developing economies where the opposite seems to be true, namely the transition economies of the post Soviet era. Furthermore, I explore the role of different forms of technological heterogeneity across countries as a key determinant of the relationship between environmental quality and economic development.

To my wife Janna and my son Douglas.

To my parents Paulo and Dinaura.

To Tia Anninha.

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List of Abbreviations

CEE Central and Eastern Europe.

CO Carbon Monoxide.

CO_2 Carbon Dioxide.

EKC Environmental Kuznets Curve.

GDP Gross Domestic Product.

LDC Less Developed Country.

NIS Newly Independent States.

NO_X Oxides of Nitrogen.

SO_2 Sulfur Dioxide.

SPM Suspended Particulate Matter.

TFP Total Factor Productivity.

Chapter 1

INTRODUCTION

This dissertation investigates environmental quality and economic development when pollution is treated as an externality generated in the production sector and affecting the consumption sector. This framework is adequate for an important group of industrial pollutants affecting both air, water and soil quality such as sulfur dioxide (SO_2), oxides of nitrogen (NO_X), heavy metals, and oils and greases among others.

Several studies indicate that when pollution control is technically and institutionally feasible, both emissions and ambient concentrations of these industrial pollutants increase at lower stages of development, reach a peak and eventually start to decrease. This pattern describes an inverted U-shaped curve known as the environmental Kuznets curve (EKC). Using panel data for urban areas in different countries Grossman and Krueger (1995) estimate the EKC for ambient concentrations of several air and water indicators of pollution. According to their estimates, total pollution starts to fall below \$8000 per capita for most pollutants. Using aggregate national data Selden and Song (1994) estimate the EKC for per capita emissions of SO_2, NO_X, suspended particulate matter (SPM) and carbon monoxide (CO). They find that the EKC exists, but with turning points above \$9000. The EKC does not apply to every measure of environmental quality. For some pollutants, such as carbon dioxide (CO_2), emissions seem to increase with income without any sign of a downward trend. However, following the literature on the EKC, the focus of this dissertation is on the conventional industrial pollutants.

In a recent paper, Borghesi (1999) provides a review of the early and recent empirical studies addressing the EKC. The author points at the evidence collected so far as well as some problems with data and econometric estimation that are present in these studies. She concludes that even though the experience of more developed countries points to the existence of the EKC, the absence of long enough time series on environmental quality compromise the conclusions that the EKC is universal and that less developed countries (LDCs) will experience improved environmental quality as incomes rise. This qualification stems from the fact that most studies rely on cross-sectional data. Econometric exercises performed in this context will produce an inverted U-shaped curve for pollution as an artifact, but they do not provide an underlying explanation for a necessary linkage between income and environmental quality. This dissertation develops such an explanation within a theoretical framework, showing that the EKC is consistent with Pareto optimality and that environmental quality eventually rebounds as income grows.

In another recent study, Harbaugh et al. (2000) reexamine the empirical evidence on the EKC using a variety of functional forms and new data. They conclude that the EKC hypothesis is sensitive to these changes and they do not identify any well defined relationship between income and the environment. However, the authors recognize that the functional specifications used in their study are not justified by any theoretical framework, introducing possible misspecifications and invalidating the conclusions. Furthermore, as is common in most other panel studies on the EKC - if not all of them - they fail to recognize that country-specific characteristics may be importantly correlated with national income as shown by Parente and Prescott (1994). This pattern of correlation may produce biased and inconsistent estimates (Hausman and Taylor (1981)), thus invalidating the results.

Despite the problems with the empirical studies produced so far, there is a consensus that environmental quality has improved in regions such as Western Europe and North America in the last decades. For that reason, much effort has been directed to the development of a theoretical explanation of the EKC, especially to the question of whether the EKC is consistent with Pareto optimality (Harbaugh et al., 2000). This dissertation aims generally to advance the theoretical understanding of the EKC by analyzing the optimal choice of consumption and environmental protection.

The three major chapters of this dissertation study Pareto optimal environmental quality in a dynamic economy under two different scenarios. The first scenario considers a social planner that maximizes the intertemporal stream of social welfare. Society values both consumption and environmental quality whereas capital produces goods and generates pollution. Environmental quality and capital are treated as stock variables and optimality in the steady state of the economy requires that these two are in a given proportion. Chapter 2 analyzes the optimal path to the steady state when a country starts with a small stock of capital and a large stock of environmental quality. This initial condition is typical for most developed countries and LDCs and produces the EKC along an optimal path to the steady state.

Chapter 3 studies the opposite case when, at time zero, a country starts with a small stock of the environment relative to the stock of capital. More than a theoretical curiosity, this case represents in a general way the transition economies of Central and Eastern Europe. The widespread perception is that "the collapse of communism unveiled levels of environmental degradation that were unexpected for the level of economic development of the region" (Panayotou, 1999, p. 403). Chapter 3 identifies the optimal path to the steady state in transition economies and identifies a policy rule that is consistent with attainment of the optimal ratio of capital to environmental quality.

The second scenario focuses on the implications of technology adoption for environmental quality. As before, I investigate Pareto optimality in a dynamic economy that values both consumption and environmental quality, and devotes some of its resources to environmental protection. In chapter 4, in order to concentrate on the main issues of interest, I abstract from endogenous growth models and analyze the effect on environmental quality, environmental protection effort, consumption and capital of the adoption of different technologies. To do that, I perform comparative statics on the steady state of the model by allowing three types of technological heterogeneity: (i) differences in total factor productivity (TFP); (ii) differences in environmental preservation efficiency; and (iii) differences in pollution intensity of capital. This exercise helps explain the discrepancy of incomes and environmental quality in different countries. Furthermore, it provides guidance for empirical research on environmental quality and economic development that uses data from different countries. Chapter 4 of this dissertation shows how country-specific characteristics in the form of barriers to technology adoption and resulting different total factor productivity (TFP) may actually help explain the EKC. Differences in TFP are believed to be crucial in explaining heterogeneous income levels around the world (Parente and Prescott (1994)), and should not be left out in a cross country study that relies on economic development to explain environmental quality.

In summary, this dissertation contributes to the construction of a theoretical framework for understanding the relationship between environmental quality and economic development. I consider not only the traditional case of nations that start their development with a small stock of capital and a large stock of the environment, but also an important group of developing economies where the opposite is true, namely the transition economies of the post Soviet era. Furthermore, it explores the role of different forms of technological heterogeneity across countries as a key determinant of the relationship between environmental quality and economic development. Finally, this dissertation provides a theoretical framework for the analysis of the development-environment relationship using cross-section/panel data.

Chapter 2

ECONOMIC GROWTH AND THE DYNAMICS OF ENVIRONMENTAL QUALITY

2.1 INTRODUCTION

The linkages between economic growth and environmental quality have drawn significant attention recently. For example, Gene M. Grossman and Alan B. Krueger (1995) and Thomas M. Selden and Daquing Song (1994) document an empirical relationship between economic development and a large number of industrial pollutants, describing a pattern known as the environmental Kuznets curves (EKC). Cross–sectionally across countries, as income grows both ambient concentrations and emissions first rise and then fall, generating an inverted U-shaped relationship. Surprisingly, the underlying economic forces that could produce such a relationship have not been thoroughly investigated.

This paper develops a simple dynamic model of economic growth and environmental quality. It advances beyond prior work by explaining the consistency of the EKC with Pareto optimality based on the relative scarcity of capital during a country's development, and not on the restrictive assumptions of intergenerational conflicts, ill-defined property rights or higher pollution intensity of more productive capital. We solve for the transitional dynamics and show that the model can account for important empirical regularities in the relationship between growth and environmental quality. In the model, individuals care about both consumption of a private good and environmental quality which is a public good. A by-product of production is pollution which degrades environmental quality. However, society can devote resources toward environmental protection — pollution abatement expenditures, development of nature reserves, and the like — that offset the effects of pollution. We solve for the paths of consumption and environmental protection expenditures that maximize social welfare. The solution to the social planner's problem is consistent with three empirical regularities. First, as implied by the EKC, environmental quality decreases during the initial stages of economic development, but eventually the trend reverses and environmental quality rebounds. Second, stocks of capital and environmental quality eventually reach threshold levels that prompt society to begin to devote resources toward environmental protection. Thereafter, society devotes increasingly more resources to environmental protection, so that environmental quality improves. Third, the increased expenditures on environmental protection reduce growth rates. Accordingly, the model's predictions are consistent with the empirical regularity that growth rates in many developing economies without environmental regulation are higher than those in advanced economies with effective environmental standards.

The Pareto optimal path for the economy suggests an optimal policy program. During the initial stages of development, the optimal expenditures on environmental protection are zero, so a decentralized competitive economy would generate the social optimum. Eventually, the capital stock grows enough and the environment is degraded sufficiently that society should begin to devote resources toward improving environmental quality. At that point, government intervention is required. Accordingly, the model predicts that regulation and expenditures on environmental protection should be negligible or absent during the initial stages of economic development. However, once government intervention becomes optimal, governments should impose ever-more stringent controls. This program, too, is consistent with empirical observation. In the U.S., for example, the Environmental Protection Agency (EPA) as well as substantial regulation and significant expenditures on environmental protection came to being only in the 1970s, long after the introduction of regulations designed to deal with other types of market failure (Paul E. Portney, 1990). This historical pattern appears in other developed nations, and most industrializing countries have little in the way of effective environmental protections.

Previous attempts to model the EKC have relied on restrictive assumptions. Andrew John and Rowena Pecchenino (1994) and Larry Jones and Rodolfo Manuelli (1994) rely on intergenerational conflicts to explain the EKC. We assume instead an infinitely lived dynasty without intergenerational conflicts. As Nancy L. Stokey (1998) points out, this assumption seems natural here because it captures altruism between generations and the recurrent concern about the quality of the environment that future generations will inherit.

More recently, Nancy L. Stokey (1998) derives the conditions for the existence of the EKC based on the assumption that more productive technologies are more pollution intensive. However, Stokey's underlying assumption of a positive relationship between productivity and pollution appears to be at odds with the trend in more advanced economies toward more productive, less pollution-intensive technologies. For example, Valérie Reppelin-Hill (1999) documents the diffusion of a cleaner and more productive technology for the production of steel. Indeed, as with Stokey's framework, most models assume that pollution is an increasing and convex function of capital (Bruce A. Forster, 1973b, Thomas M. Selden and Daquing Song, 1995, and Daniel F. Spulber, 1985), thus increasing the gap between theory and actual trends on the pollution intensity of capital. We sever this link between capital and environmental degradation by distinguishing the (linear) impact of the capital stock on pollution, and the expenditures by society on environmental quality. As a result, we do not need to make the same convexity assumptions.

Building on the simple dynamic models by Bruce A. Forster (1973a and 1973b), Thomas M. Selden and Daquing Song (1995) show the possibility of a "J" curve for abatement expenditures and an inverted "U" curve for pollution. In their model, individuals value consumption and dislike pollution, which is increasing and convex in capital and decreasing and convex in abatement expenditures. They show that if the marginal utility of consumption is initially higher than the marginal benefit from abatement, then the EKC for pollution and a "J" curve for abatement expenditures may result. However, the authors indicate that this need not always occur, depending on the rate of growth of capital and consumption, and the response of pollution to abatement effort. By comparison, in this paper, consumers value both consumption and environmental quality, which is treated as a stock variable. This formulation allows us to build a simple model that produces a definitive path for environmental quality and environmental expenditures consistent with the empirical evidence.

A. Lans Bovenberg and Sjak Smulders (1995) and Elamin H. Elbasha and Terry L. Roe

(1996) develop endogenous growth models with an environmental variable, but they focus on the steady state of the economy and produce monotone paths for environmental quality. They therefore fail to produce the empirical regularity described by the EKC.

In another stream of literature, some authors argue that ill-defined property rights at early stages of economic development are a major culprit for limited investment and income, and for free access to natural resources and consequently increased environmental degradation (for example, Graciela Chichilnisky, 1994, and Ramon Lopez, 1994, consider natural resources use and property rights). This trend is reversed when ownership risk is secured, thus promoting economic growth and environmental protection. According to this argument, the evolution of property rights would then explain the time path for environmental quality and income, therefore delineating the EKC. However, Henning Bohn and Robert T. Deacon (2000) stress the limitations of this argument by pointing out that ill-defined property rights will lead to natural resource conservation when degradation can take place only with substantial amounts of accumulated capital. This is true, for example, with oil extraction and important industrial pollutants. Furthermore, despite the improvements in environmental indicators such as air and water quality in more developed nations over the past decades, property rights of these public goods are typically far from secured, or even well defined. We therefore ignore the property rights approach when explaining the EKC.

Our argument rests on the simple premise that the optimal investment strategy of a nation responds to the relative abundance of different types of capital. When environment is abundant relative to productive capital, the latter will be built up, resulting in pollution and a degradation of environmental capital. As productive capital accumulates and environment grows less plentiful, investment in the latter increases. This simple and intuitive insight is sufficient to produce the EKC as an optimal path for a developing economy.

This chapter is organized as follows: Section 2.2 describes the model and section 2.3 investigates its steady state. Section 2.4 analyzes the transition to the steady state and Section 2.5 draws conclusions.

2.2 MODEL

Consider an economy modeled in continuous time t where each of the N identical individuals values consumption of a private good, c_t, and a pure public good, environmental quality, E_t. For simplicity, we assume that instantaneous individual utility is given by

$$u(c_t, E_t) = \alpha \ln(c_t) + (1-\alpha)\ln(E_t),$$

where the weight α on private consumption in utility is between zero and one. Individuals have a constant discount rate $0 < \rho < 1$.

Let K_t be the aggregate capital stock at time t. The consumption good is produced using the capital input according to a linear technology,

$$F(K_t) = AK_t,$$

where $A > 0$. Pollution, $P(K_t)$, is a by-product of production. For simplicity, we assume that pollution is a linear function of the capital employed in production,

$$P(K_t) = PK_t.$$

Pollution degrades the level of environmental quality in the economy. However, society can mitigate the effects of pollution on environmental quality by devoting resources, $\pi_t \geq 0$, to environmental protection efforts. These environmental protection expenditures could include expenditures on pollution abatement, development of nature reserves, protection of endangered species, etc. Accordingly, environmental quality evolves over time according to

$$\dot{E}_t = -PK_t + \Pi\pi_t + \xi E_t,$$

where $\xi \geq 0$ allows for the natural regenerative capacity of the environment. Furthermore, ξ is assumed to be zero at the pristine state of the environment and positive otherwise. Finally, capital accumulation is the difference between production $F(K_t)$, aggregate consumption Nc_t, resources devoted to environmental protection π_t, and capital depreciation that occurs at the constant rate $0 < \delta < 1$:

$$\dot{K}_t = AK_t - Nc_t - \pi_t - \delta K_t.$$

We assume that the following transversality condition holds:

$$\lim_{t \to \infty} e^{-\rho t}\mu_t K_t = 0,$$

where μ_t is the current value of the time t shadow value of capital.

In this economy, we assume that a social planner seeking to maximize per capita lifetime utility chooses laws of motion for consumption and environmental protection that solve:

$$\max_{c_t, \pi_t} \int_0^\infty e^{-\rho t} N[\alpha \ln(c_t) + (1-\alpha)\ln(E_t)]\, dt$$

subject to the laws of motion on environmental quality and capital accumulation

$$\dot{E}_t = -PK_t + \Pi \pi_t + \xi E_t,$$

$$\dot{K}_t = AK_t - Nc_t - \pi_t - \delta K_t,$$

$$\pi_t \geq 0,$$

and initial conditions

$$K_0, E_0.$$

The associated current value Lagrangian is given by

$$\mathcal{L}_t = N[\alpha \ln(c_t) + (1-\alpha)\ln(E_t)] + \lambda_t[-PK_t + \Pi\pi_t + \xi E_t] + \mu_t[AK_t - Nc_t - \pi_t - \delta K_t] + \theta_t \pi_t,$$

where μ_t is the shadow value of capital, λ_t is the shadow value of environmental quality, and $\theta_t \geq 0$ captures the non-negativity of environmental protection efforts.

The necessary conditions for a maximum are (see Appendix A for the derivation of the necessary and transversality conditions):

$$\mu_t = \frac{\alpha}{c_t}, \tag{2.1}$$

$$\lambda_t = \frac{\mu_t - \theta_t}{\Pi}, \tag{2.2}$$

$$\dot{\lambda}_t = \lambda_t(\rho - \xi) - N\frac{(1-\alpha)}{E_t}, \tag{2.3}$$

$$\dot{\mu}_t = \mu_t\left(\frac{P}{\Pi} + \rho + \delta - A\right) - \frac{P\theta_t}{\Pi}, \tag{2.4}$$

and the transversality condition:

$$\lim_{t\to\infty} e^{-\rho t} e^{\left(\frac{P}{\Pi}+\rho+\delta-A\right)t}\left(\tilde{\mu} - \frac{P}{\Pi}\int_0^t e^{-\left(\frac{P}{\Pi}+\rho+\delta-A\right)\tau}\theta_\tau d\tau\right) K_t = 0, \tag{2.5}$$

where $\tilde{\mu}$ is a constant.

At the optimum, equation (2.1) shows that the shadow value of the stock of capital equals the marginal utility from consumption, i.e., the marginal contribution of capital to social welfare must equal the marginal utility from additional consumption produced with the extra unit of capital. Equation (2.2) indicates the optimal trade-off between the stock of environmental quality and stock of capital, taking the marginal cost of improving environmental quality and the slackness condition into consideration.

Equations (2.3) and (2.4) form a system of differential equations with the laws of motion governing the shadow values of environmental quality and capital. At any given time, time changes in the shadow value of the environment are positively related to the discount rate and negatively related to the natural rate of recovery and marginal utility of environmental quality. Changes in the shadow value of the stock of capital, on the other hand, are positively related to the cost of marginal pollution in terms of environmental quality, the discount rate and the depreciation rate, and negatively related to the marginal product of capital.

2.3 STEADY STATE

In the steady state of the economy, every variable of the system grows at a constant rate. For analysis, we assume an interior solution to the maximization problem above. The associated necessary conditions and the transversality condition are given in equations (2.1) through (2.5) with $\theta_t = 0$. Appendix B provides a full derivation of the steady state results, which are summarized below:

The resulting optimal rate of growth of consumption is:

$$\frac{\dot{c}_t}{c_t} = \left(A - \frac{P}{\Pi} - \rho - \delta\right). \tag{2.6}$$

Assuming that the marginal product of capital is high enough to cover the marginal environmental protection cost per unit of capital, the discount rate and the capital depreciation rate, i.e., $\varphi \equiv \left(A - \frac{P}{\Pi} - \rho - \delta\right) > 0$, consumption will be increasing at the constant rate φ.

The necessary conditions also require a constant ratio between consumption and environmental quality for an optimal solution at each time t:

$$\frac{c_t}{E_t} = \left(A - \frac{P}{\Pi} - \delta - \xi\right) \frac{\alpha}{\Pi N(1-\alpha)},$$

or in a more compact notation $E_t = \phi c_t$, where ϕ is the inverse of the right hand side of the expression above. Also, by assumption, $\rho > \xi$. This assumption not only makes the fraction c_t/E_t positive, since $\varphi > 0$, but will prove useful below in the derivation of the transitional dynamics of the economy.

The results above, the initial conditions and the laws of motion for K and E, and the transversality condition imply the optimal path of the variables of the model over the planning horizon:

$$E_t = E_0 e^{\varphi t}, \tag{2.7}$$

$$c_t = \frac{E_0}{\phi} e^{\varphi t}, \tag{2.8}$$

$$K_t = \left(\frac{N}{\phi} + \frac{(\varphi - \xi)}{\Pi} \right) \frac{E_0}{\rho} e^{\varphi t}, \tag{2.9}$$

$$\pi_t = \left[\frac{(\varphi - \xi)}{\Pi} + \frac{P}{\Pi} \left(\frac{N}{\phi} + \frac{(\varphi - \xi)}{\Pi} \right) \frac{1}{\rho} \right] E_0 e^{\varphi t}. \tag{2.10}$$

Finally, using (2.7) and (2.9), a necessary condition for the optimal solution to hold in the steady state is that the ratio between the stocks of capital and environmental quality must be constant as follows:

$$\frac{K_t}{E_t} = \left(\frac{N}{\phi} + \frac{(\varphi - \xi)}{\Pi} \right) \frac{1}{\rho}. \tag{2.11}$$

Assuming that $\varphi > \xi$ yields a sufficient, but not necessary, condition for all the variables to be growing at the same rate γ^* in the steady state: If equation (2.11) holds, then a steady state with balanced growth results, $\gamma_c^* = \gamma_\pi^* = \gamma_K^* = \gamma_E^* = \gamma^* = \varphi$.

Clearly, in general, equality will not hold in equation (2.11) at time zero, and analysis of the transitional dynamics from the initial conditions to the steady state of the economy becomes a relevant exercise. This issue is addressed in the next section.

2.4 TRANSITIONAL DYNAMICS

This section investigates the transitional dynamics of the economy described in the previous sections due to an imbalance on the initial conditions for capital and environmental quality.

Typically, a country starts its process of economic development with a small stock of capital (i.e., small K_0) and a pristine environment (i.e., large E_0). In terms of equation (2.11), $\frac{K_0}{E_0} < \left(\frac{N}{\phi} + \frac{(\varphi-\xi)}{\Pi}\right)\frac{1}{\rho}$.

The social planner wishes to get to the balanced endogenous growth path described in section 2.3 as quickly as possible. This implies changing the initial ratio of capital to environmental quality so as to achieve equality in equation (2.11) at the closest date possible. One conceivable way to achieve this goal is to destroy part of the environmental stock and possibly convert that into capital so that equality in equation (2.11) is immediately achieved. However immediate conversion of the stock of the environment into capital is only possible to a limited extent in extractive societies, and it is more realistic to assume that these jumps are negligible and can be approximated by finite positive rates of investment in K_t and finite negative rates of growth of E_t. Negative growth in E_t will result from simultaneous increase in the capital stock and pollution, and zero expenditures on environmental protection, interpreted as investment in the stock of the environment.

Under the circumstances described above, the social planner recognizes the relative scarcity of K, thus increasing the stock of capital and allowing environmental quality to decrease as quickly as possible. This implies that the non-negativity constraint on environmental expenditures, π_t, is binding, and the term θ_t in the necessary conditions is positive. Furthermore, from equation (2.4), the shadow value of capital decays at a faster rate when θ_t is positive:

$$\frac{\dot{\mu}_t}{\mu_t} = \left(\frac{P}{\Pi} + \rho + \delta - A\right) - \frac{P\theta_t}{\Pi\mu_t} < 0. \qquad (2.12)$$

Equation (2.12) is consistent with higher rates of growth observed at earlier stages of development, when the capital stock of the economy is small relative to its environmental stock.

Manipulation of the necessary conditions produces the optimal consumption path during the transition to the steady state ratio of capital to environmental quality (see Appendix C):

$$c_t = \frac{c_0 e^{\varphi t}}{1 - \frac{P c_0}{\Pi \alpha} \int_0^t \theta_\tau e^{\varphi \tau} d\tau}, \tag{2.13}$$

where c_0 is consumption per capita at time zero and θ_t is such that $\frac{P c_0}{\Pi \alpha} \int_0^t \theta_\tau e^{\varphi \tau} d\tau < 1$ for every t. Additionally, the equations of motion for capital ($\dot{K}_t = AK_t - Nc_t - \delta K_t$) and environmental quality ($\dot{E}_t = -PK_t + \xi E_t$) during the transition yield:

$$K_t = -Ne^{(A-\delta)t} \int_0^t c_\tau e^{-(A-\delta)\tau} d\tau + K_0 e^{(A-\delta)t}, \tag{2.14}$$

$$E_t = -Pe^{\xi t} \int_0^t K_\tau e^{-\xi \tau} d\tau + E_0 e^{\xi t}. \tag{2.15}$$

During the transition, when environmental quality is abundant relative to capital, the shadow value of capital, μ_t, will be decreasing by equation (2.12), implying that the stock of capital K_t will be increasing. To see that μ_t and K_t are inversely related, we solve for consumption in the equation of motion of capital, $c_t = \frac{(A-\delta)K_t - \dot{K}_t}{N}$, and substitute the right hand side into the necessary condition (2.1): $\mu_t = \frac{\alpha}{c_t}$. Rearranging and differentiating K_t with respect to μ_t yields: $\frac{\partial K_t}{\partial \mu_t} = -\frac{\alpha N}{\mu_t^2 (A-\delta)} < 0$. Furthermore, we assumed that $\xi = 0$ at the pristine level of the natural environment, so environmental quality may initially stay close to the pristine level, but will eventually start to decrease as the capital stock increases. Subsequently, as environmental quality falls, E_t is concave in t, highlighting increasing marginal damages to the environment as time elapses. The transition to the steady state is complete at the finite date t_1. At that time, the social planner faces a larger stock of capital than at time zero and consequently more pollution. To offset pollution and promote environmental improvements as described by the optimal steady state solution, a strictly positive level of environmental expenditures π_{t_1} is required. Furthermore, consumption begins to grow at a reduced rate. Proposition 1 summarizes these results.

Definition 1 *Environmental quality is abundant at time t if and only if the ratio of capital to environmental quality is smaller than the optimal steady state ratio, i.e.,* $\frac{K_t}{E_t} < \left(\frac{N}{\phi} + \frac{(\varphi-\xi)}{\Pi}\right)\frac{1}{\rho}$.

Proposition 1 *For a country starting its planning horizon with abundant environmental quality:*

(i) for a sufficiently large initial stock of capital K_0*, environmental quality is decreasing and concave in time during the transition to the steady state. Furthermore, the transition takes a finite period of time — there is a finite time* t_1 *such that environmental quality is increasing at the constant rate* φ *for every* $t \geq t_1$*;*

(ii) environmental expenditures π_t *are initially (a) zero from time zero to* t_1*, and then (b) increasing at the constant rate* φ *at dates* $t \geq t_1$*. Furthermore,* π_t *is discontinuous at* t_1*;*

(iii) the rate of growth of consumption from time zero to t_1*,* γ_c*, exceeds its (constant) rate of growth* φ *at dates* $t \geq t_1$*.*

Proof:

(i) At t_0, the fastest transition to the steady state ratio of capital to environmental quality requires zero expenditures on environmental protection π_t. Hence, the equation of motion of environmental quality becomes $\dot{E} = -PK + \xi E$. Choose K_0 large enough so that $\dot{E} < 0$.

Then, $\ddot{E} = -P\dot{K} + \xi\dot{E} < 0$, since $\dot{K} > 0$ during the transition. Therefore, environmental quality E_t is decreasing and concave in time during the transition to the steady state. To see that the transition to the steady state is done in finite time, notice that since environmental quality is decreasing and capital is increasing, $E_t \to 0$, $K_t \to \infty$ and the ratio $\frac{K_t}{E_t} \to \infty$ as $t \to \infty$. Thus, starting with abundant environmental quality at t_0, there exists a $t_1 < \infty$ such that $\frac{K_{t_1}}{E_{t_1}} = \left(\frac{N}{\phi} + \frac{(\varphi-\xi)}{\Pi}\right)\frac{1}{\rho}$. That is, at time t_1 the optimal steady state ratio of capital to environmental quality is reached and the solution to the social planner's problem derived in section 2.3 indicates that environmental quality grows at the constant rate φ.

(ii) Zero expenditures on environmental protection when environmental quality is abundant follows directly from the fastest transition to the optimal steady state ratio of capital to environmental quality. Likewise, at time t_1 defined in (i), the steady state solution to the social planner's problem indicates that environmental expenditures, π_t, grow at the constant rate φ. To see that π_t is discontinuous at t_1, notice that $\pi_t = 0$ for $0 \leq t < t_1$ and $\pi_t = \left[\frac{(\varphi-\xi)}{\Pi} + \frac{P}{\Pi}\left(\frac{N}{\phi} + \frac{(\varphi-\xi)}{\Pi}\right)\frac{1}{\rho}\right] E_0 e^{\varphi t}$ for $t \geq t_1$. Therefore,

$$\lim_{t \to t_1^-} \pi_t = 0,$$

and

$$\lim_{t \to t_1^+} \pi_t = \left[\frac{(\varphi-\xi)}{\Pi} + \frac{P}{\Pi}\left(\frac{N}{\phi} + \frac{(\varphi-\xi)}{\Pi}\right)\frac{1}{\rho}\right] E_0 e^{\varphi t_1} > 0,$$

by assumption that the term within brackets in the last expression is strictly positive, since $\pi_t \geq 0$.

(iii) Define $\gamma_c^* \equiv \frac{\dot{c}}{c} = \varphi$ as the rate of growth of consumption in the steady state, i.e., for every $t \geq t_1$, with t_1 defined in (i). Next differentiate the necessary condition (2.1) with respect to time to obtain $\dot{\mu}_t = -\frac{\alpha \dot{c}_t}{c_t^2}$. Using (2.1) and rearranging yields $\gamma_\mu \equiv \frac{\dot{\mu}}{\mu} = -\frac{\dot{c}}{c} \equiv -\gamma_c$. Hence, from equation (2.12), during the transition, $\gamma_c = \left(A - \frac{P}{\Pi} - \rho - \delta\right) + \frac{P\theta_t}{\Pi\mu} = \varphi + \frac{P\theta_t}{\Pi\alpha} c_t > \varphi = \gamma_c^*$. ■

In accordance with Proposition 1 (i) and (ii), Figure 2.1 depicts the shape of the Pareto optimal curves for environmental quality and environmental expenditures as functions of time when a country starts its planning horizon with abundant environmental quality. These paths are consistent with the environmental Kuznets curve and the delayed environmental expenditures in most countries.

In Figure 2.1, environmental quality decreases during a transition phase. It is concave in time during the transition reflecting the effect of an increasing stock of productive capital accompanied by zero environmental expenditures. When the optimal ratio of capital to the environment is reached, environmental expenditures become positive and environmental quality rebounds. From this date on, environmental quality, environmental expenditures, capital and consumption all grow at a common constant rate.

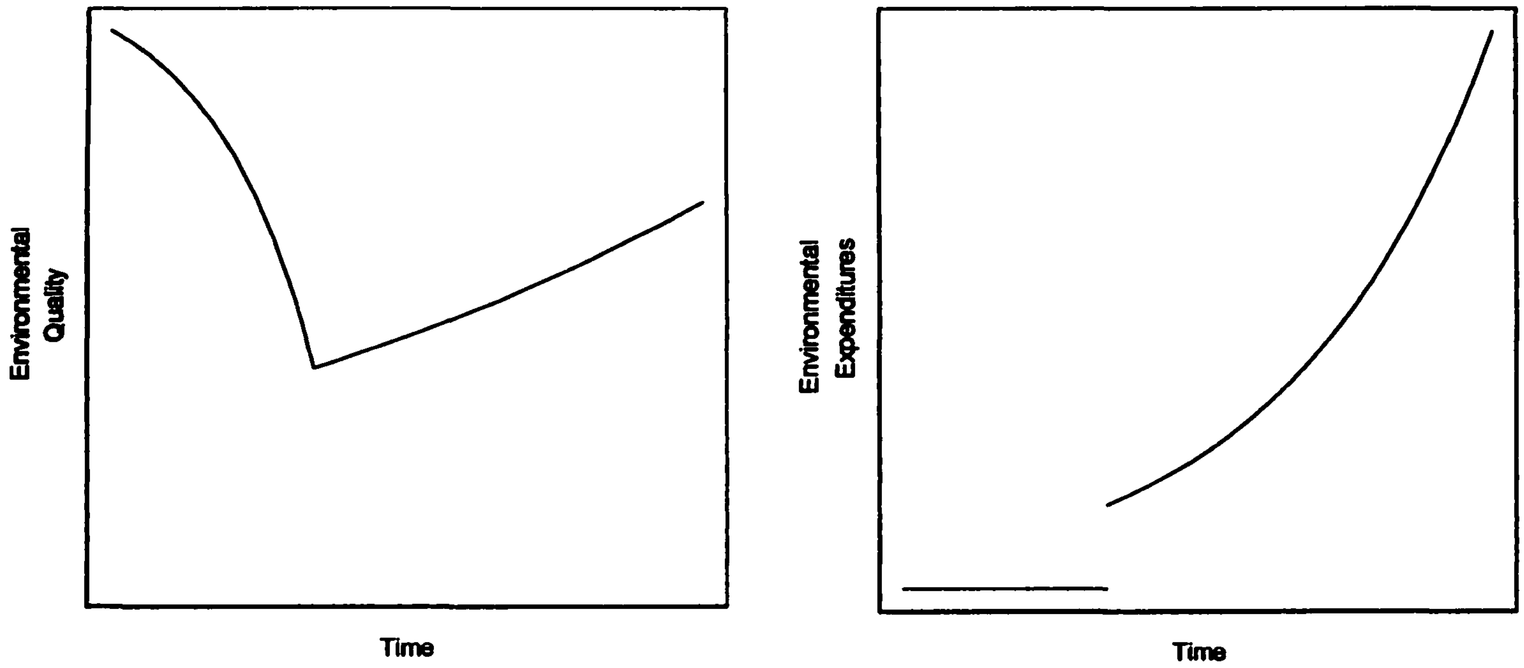


Figure 2.1: Environmental Quality and Environmental Expenditures

2.5 CONCLUSION

This paper explores the underlying causes of the relationship between economic growth and environmental quality. The model is distinctive in its simplicity and freedom from institutional details, intergenerational conflicts, and counterfactual assumptions about technology. The results of the model are consistent with three important empirical facts: (i) environmental quality decreases at early stages of development at increasing rates but eventually starts to increase; (ii) preservation effort is usually negligible or absent at early stages of development, when capital accumulation is more crucial to economic growth; and (iii) economic growth rates are typically high at early stages of economic development and decrease thereafter.

We characterize the time path for environmental quality as the economy develops. With the economy growing and capital accumulating, environmental quality initially declines at an increasing rate. However, once the optimal steady state ratio of capital to environmental quality is realized, more resources are devoted to environmental protection and environmental quality rebounds. The eventual shift toward environmental protection reduces the rate of economic growth and is reflected by a smaller rate of growth of consumption and a smaller rate of decay in the shadow value of capital.

Chapter 3

OPTIMAL DYNAMICS OF ENVIRONMENTAL QUALITY IN ECONOMIES IN TRANSITION

3.1 INTRODUCTION

The transition economies of Central and Eastern Europe (CEE) and the Newly Independent States (NIS) experience higher levels of pollution and energy intensities of GDP relative to both more developed nations and economies with comparable income levels. Besides the typically acknowledged effects of poor environmental quality on human life quality (Krupnick et al., 1996 and Hughes and Lovei, 1999), environmental concerns actively influence the course of economic transition. For example, environmental liabilities of state-owned enterprises pose real obstacles to privatization (Bluffstone and Panayotou, 1997), and a clear trade-off between environmental protection and employment frequently emerges (Markandya, 1997). Despite the relevance of environmental variables to transition economies, most studies addressing this issue are empirical or analyze the effect of environmental protection on economic variables, without deriving the optimal path of environmental quality during the transition. This chapter presents a theoretical framework within which both economic and environmental transitions can be analyzed.

This chapter builds on the dynamic model of chapter 2 to describe some basic characteristics of environmental quality in the transition economies of Europe and Central Asia. Beginning in the late 1980s and early 1990s, the overall perception was that "the collapse of communism unveiled levels of environmental degradation that were unexpected for the level of economic development of the region" (Panayotou, 1999, p. 403). Those countries are therefore characterized here as economies starting their planning horizons with a relatively large capital stock and poor environmental quality[1]. Furthermore, this chapter derives the optimal path of environmental quality towards the steady state of the economy. In particular, a policy rule leading to the optimal ratio of capital to environmental quality is obtained.

The remainder of this chapter is organized in five sections. Section 3.2 briefly reviews the economic and environmental scenario of transition economies in Europe and Central Asia. In section 3.3 a formal dynamic model of welfare maximization of an economy whose representative agents value consumption and environmental quality is developed. Section 2.3 derives the steady state of the economy, whereas section C analyzes the path of transition economies to the steady state. Finally, section 5 presents some concluding remarks.

[1]Such imbalance between capital and environmental quality is even more pronounced if capital is broadly defined to include human capital.

Table 3.1: Environmental Pressures in CEE in the Late 1980s.

Pollution and energy intensity of GDP	CEE6	EC12
Energy intensity of GDP, TOE/$1000	0.77	0.23
Industrial solid waste, tons/$	1.0	0.4
Wastewater, m^3/$	83	24
Gases (excl. CO_2), kg/$1000	51	24
Dust, kg/$1000	13	1

CEE6: Bulgaria, Czechoslovakia, GDR, Hungary, Poland and Romania.
EC12: European Community of the Twelve.
TOE: Ton of oil equivalent.

Source: Zylicz (1998)

3.2 ENVIRONMENTAL TRANSITION IN CEE AND NIS

To set the stage for the analysis, it is instructive to highlight some common facts accompanying the evolution of environmental quality and the economic scenarios of the transition economies. Just prior to the beginning of transition to market economies, both CEE countries and the NIS had reached pollution and environmental degradation levels well above those observed in market economies with comparable income. Table 3.1 compares the economic pressures on the environment in the CEE countries just before the beginning of their economic transition to those pressures in the European Community. Energy intensity of GDP in CEE is more than three times that of the European Community, and pollution levels per dollar of output are also much higher in the former group of nations.

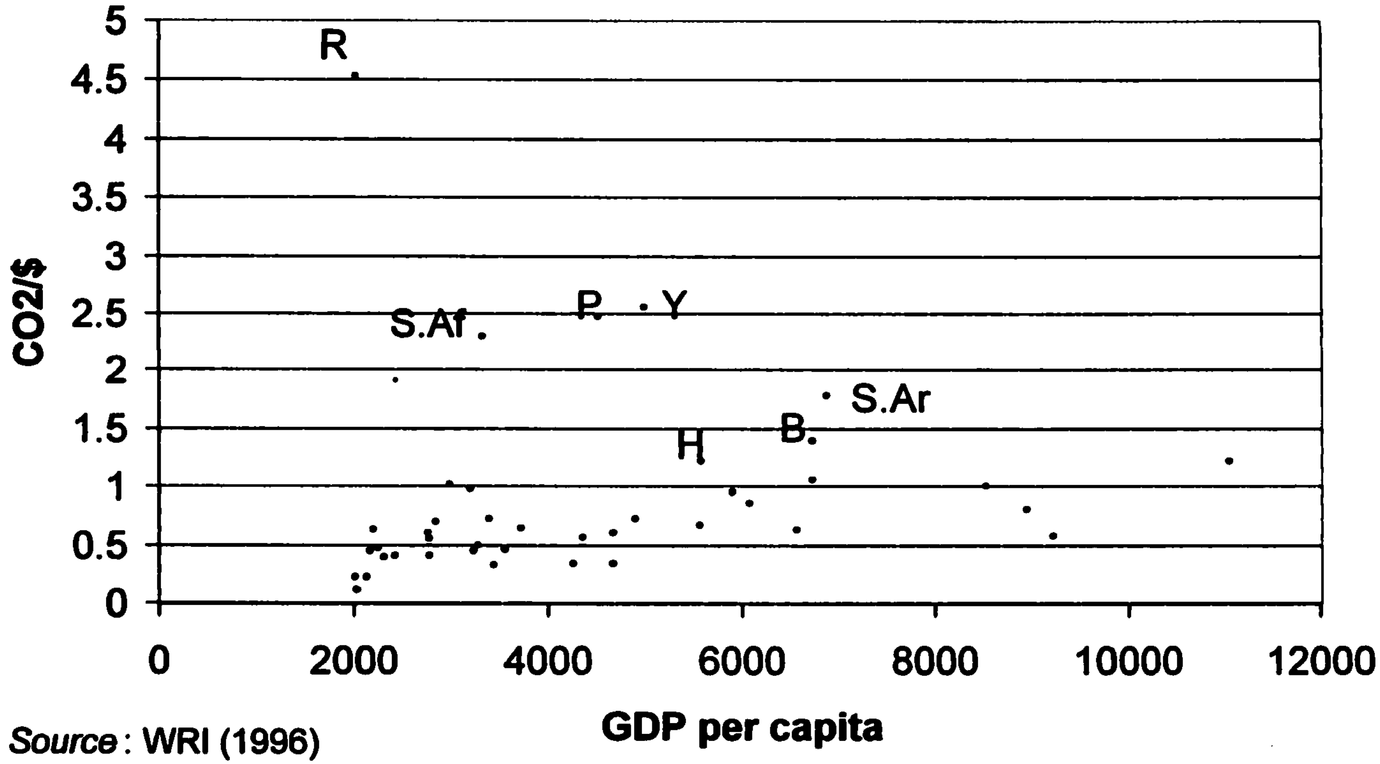
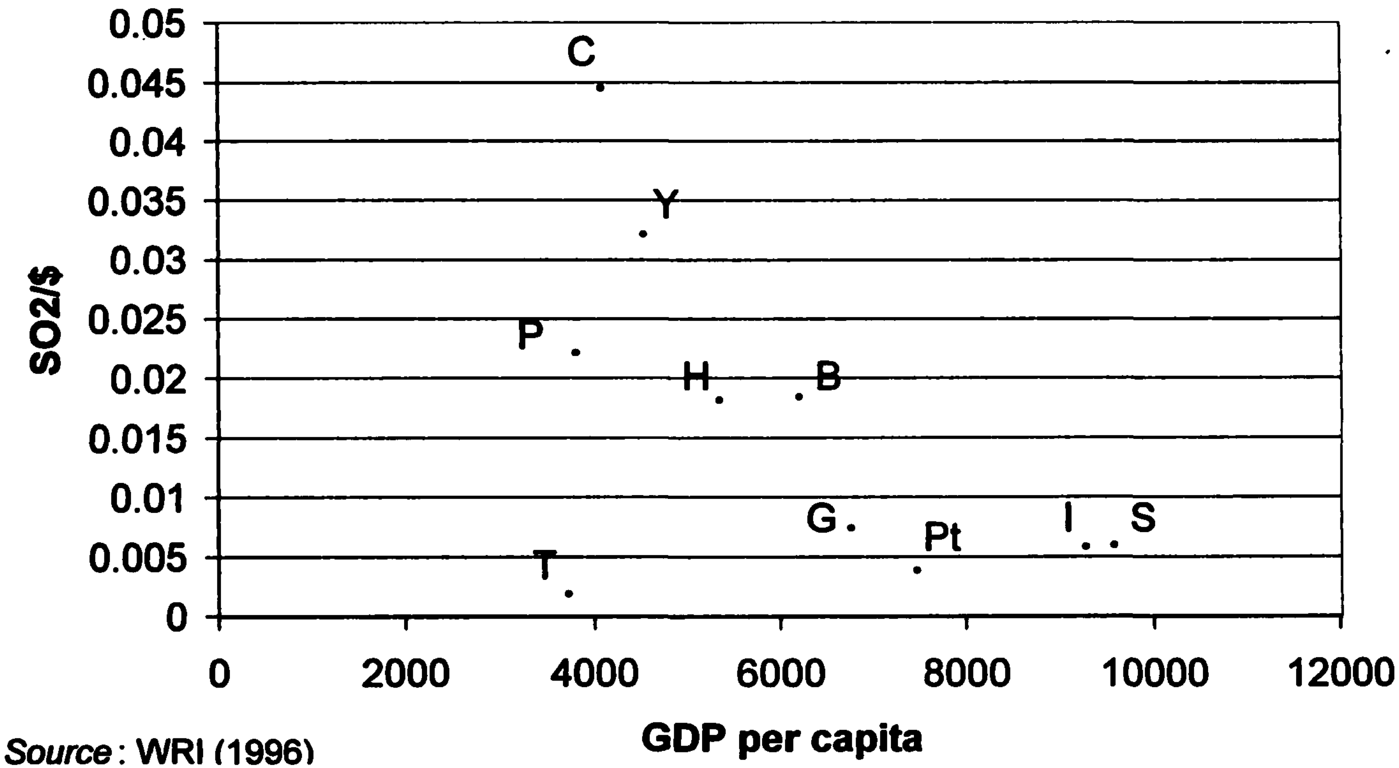


Figure 3.1: Industrial CO_2 Intensity of GDP and Income - 1989.



Source: WRI (1996)

Figure 3.2: SO_2 Intensity of GDP and Income - 1990.

A similar scenario is illustrated in Figures 3.1 and 3.2 , with transition economies indicated by full dots. Figure 3.1 plots industrial CO_2 emissions per dollar of GDP against income per capita in five transition economies (Romania, Poland, Federal Republic of Yugoslavia, Hungary and Bulgaria) and other thirty six countries in 1989. Figure 3.1 indicates that industrial CO_2 emissions for the transition economies of the sample are consistently higher than emissions in most other countries. Two notable exceptions are South Africa and Saudi Arabia. Figure 3.2 shows how SO_2 intensity of GDP was higher in transition economies than in other countries in a comparable income level in 1990. The countries in Figure 3.2 are Turkey (T), Poland (P), Czech Republic (C), Federal Republic of Yugoslavia (Y), Hungary (H), Bulgaria (B), Greece (G), Portugal (Pt), Ireland (I) and Spain (S). With the advent of the transition, pollution fell substantially, mainly due to large drops in GDP and investment, even though high levels still persisted.

In the policy arena, Zylicz (1998) and Hughes and Lovei (1999) suggest that not all environmental improvements were due to economic slow down in CEE countries but also to deliberate environmental protection policies, since pollution fell by more than GDP in the region. However, some qualifications at least partially undermine the the extent of the policy effectiveness argument. First, it is important to notice that industrial production, most likely the greatest source of pollution, also decreased by more than GDP and recovered more slowly than GDP (Blanchard, 1997 and Vorobyov and Zhukov, 1996). Second, as Vukina et al. (1999) indicate, changes in pollution are due not only to production levels and regulation effort, but also to changes in the composition of manufacturing activities in response to trade and price liberalization. Although these changes were not homogeneous across their sample of 12 former centrally planned economies and 13 pollutants, countries where the transition to market economies is more advanced experienced a more dramatic shift towards lower pollution and energy intensity of output as well as less polluting manufacturing activities. This phenomenon is another indicator of the limited effectiveness of environmental policy compared to market incentives for efficiency in production.

Meanwhile, concern with environmental protection was initially a major issue, but eventually gave way to other economic issues perceived as priorities (Pavlínek, 1997 and Markandya, 1997). Also, despite the widespread pressure on the environment inherited from the Soviet era, expenditures on the environment vary substantially across countries (Zylicz, 1998), reflecting a far from homogeneous approach to the environmental question in the transition economies.

Another indicator of effort to improve the environment in transition economies in the post-Soviet era are the so-called "environmental funds" used to finance environmental protection. The main source of these funds are pollution fines, pollution emission charges, waste disposal fees and energy taxes, which make them a barometer of national environmental protection effort (Vukina et al, 1999). Even though the environmental funds are not a perfect indicator of environmental protection since they ignore private expenditures on environmental quality, they provide an proxy for environmental degradation control in the countries of the region. The ratio of environmental funds to GDP define three major groups of transition economies. Those groups appear in Table 3.2. The first two groups have lower income per capita than the third group, but more significantly, they are mostly slower reformers compared to the the third group. Table 3.2 highlights the rather small percentages

Table 3.2: Environmental Funds as a Percentage of GDP in Transition Economies - 1993.

Environmental Funds in Transition Economies - 1993

% of GDP	Country
0 - 0.0084 %	Azerbaijan, Belarus, Bulgaria, Moldova, Romania, Ukraine, Uzbekistan
0.0157 - 0.0166 %	Kazakhstan, Russia
0.0953 - 0.2773 %	Czech Republic, Hungary, Poland, Slovak Republic

Source: Zylicz (1998)

of GDP corresponding to environmental funds and the variability of the policy approach to the environmental question in the region.

The results of this chapter help explain the contribution of environmental factors to the drop in GDP and capital accumulation in the beginning of the transition, and the variability of environmental policies and expenditures in the different economies in transition. Clearly, the effect of environmental factors can only partially explain the macroeconomic changes of transition economies. Other important factors such as the removal of subsidies of state firms, partial market reforms that diverted inputs to the private sector and created shortages to state firms, disorganization of markets for factors of production, public finance, law enforcement, and restructuring of production of state firms played and continue to play major roles in the economic progress of these economies (see for example, Murphy et al., 1992 and Blanchard, 1996, 1997 and Blanchard and Kremer, 1997).

3.3 MODEL

The model used here is the same as in chapter 2. The formalization of the problem and the results for the steady state are reproduced here for convenience:

$$\max_{c_t,\pi_t} \int_0^\infty e^{-\rho t} N[\alpha \ln(c_t) + (1-\alpha)\ln(E_t)]\, dt \qquad \text{subject to:}$$

$$\dot{E}_t = -PK_t + \Pi\pi_t + \xi E_t,$$

$$\dot{K}_t = AK_t - Nc_t - \pi_t - \delta K_t,$$

$$\pi_t \geq 0,$$

the initial conditions

$$K_0, E_0,$$

and the transversality condition:

$$\lim_{t\to\infty} e^{-\rho t}\mu_t K_t = 0$$

In the steady state:

$$E_t = E_0 e^{\varphi t}, \tag{3.1}$$

$$c_t = \frac{E_0}{\phi} e^{\varphi t}, \tag{3.2}$$

$$K_t = \left(\frac{N}{\phi} + \frac{(\varphi - \xi)}{\Pi}\right) \frac{E_0}{\rho} e^{\varphi t}, \tag{3.3}$$

$$\pi_t = \left[\frac{(\varphi - \xi)}{\Pi} + \frac{P}{\Pi}\left(\frac{N}{\phi} + \frac{(\varphi - \xi)}{\Pi}\right)\frac{1}{\rho}\right] E_0 e^{\varphi t}, \tag{3.4}$$

$$\frac{K_t}{E_t} = \left(\frac{N}{\phi} + \frac{(\varphi - \xi)}{\Pi}\right)\frac{1}{\rho}. \tag{3.5}$$

As before, assuming that $\varphi > \xi$ yields a sufficient - but not necessary - condition for c_t, π_t, E_t and K_t to grow at the same rate γ^* in the steady state. That is, if equation (3.5) holds, then a steady state with balanced growth results, i.e., $\gamma_c^* = \gamma_\pi^* = \gamma_K^* = \gamma_E^* = \gamma^* = \varphi$.

A key characteristic of the environmental situation of transition economies is their poor environmental quality compared to most market economies with similar income levels. In addition, these economies in transition have inherited a large stock of capital. This imbalance is represented by the left hand side of equation (3.5) larger than the right hand side at time zero. Such approximation sheds light on the transition economies of Eastern Europe and the NIS, and is analyzed in the transitional dynamics of the next section.

3.4 TRANSITIONAL DYNAMICS

This section considers the transition to the steady state of an economy that starts with a relatively large capital stock at the beginning of its planning horizon. That is:

$$\frac{K_0}{E_0} > \left(\frac{N}{\phi} + \frac{(\varphi - \xi)}{\Pi}\right)\frac{1}{\rho}.$$

This scenario is not typical in most developed and developing nations, but it may offer interesting insights to transition economies of CEE and the NIS. Using the social planner's problem as an approximation for those economies as soon as they departed from their previous political and economic systems, there is no doubt that they began their welfare-oriented programming horizon with more accumulated capital and poorer environmental quality than most nations did. This is even more true if capital is broadly defined to include human capital. As in most problems involving aggregate measures of environmental quality, there is inadequate evidence to capture the true imbalance between capital and environmental quality. Nevertheless, it is interesting to proceed with the conjecture of an economy with a relatively high stock of capital at the beginning of the planning horizon and investigate its transition to the steady state.

If discrete jumps in the stock of capital are allowed, the optimal steady state ratio of capital to environmental quality can be trivially reached in finite time by "destroying" part of the capital stock at time zero. On the other hand, in a more realistic approach such discrete jumps are assumed out and the social planner lets the capital stock depreciate at the exogenous rate δ in the Pareto optimal transition, that is $\dot{K}_t = -\delta K_t$. Equivalently, the social planner exhausts total output with consumption and preservation expenditures at each time t, implying that $\pi_t = AK_t - Nc_t$. Then, the current value Hamiltonian for the transition to the steady state becomes:

$$\mathcal{H} = N\left[\alpha \ln(c_t) + (1-\alpha)\ln(E_t)\right] + \lambda_t[-PK_t + \Pi(AK_t - Nc_t) + \xi E_t]$$

The necessary conditions for a maximum are:

$$\lambda_t = \frac{1}{\Pi}\frac{\alpha}{c_t} \tag{3.6}$$

$$\dot{\lambda}_t = \rho\lambda_t - \left[\frac{N(1-\alpha)}{E_t} + \lambda_t\xi\right] \tag{3.7}$$

Manipulation of the necessary conditions yields the system of equations for optimal consumption per capita, environmental quality and preservation effort during the transition[2]:

$$c_t = \frac{c_0 e^{-(\rho-\xi)t}}{1 - \frac{N\Pi c_0(1-\alpha)}{\alpha}\int\limits_0^t \frac{e^{-(\rho-\xi)\tau}}{E_\tau}d\tau}$$

$$E_t = -\frac{(\Pi A - P)}{(\delta+\xi)}K_0 e^{-\delta t} - e^{\xi t}\Pi N\int\limits_0^t c_\tau e^{-\xi\tau}d\tau + \left[E_0 + \frac{(\Pi A - P)}{(\delta+\xi)}K_0\right]e^{\xi t}$$

$$\pi_t = AK_0 e^{-\delta t} - Nc_t$$

More interestingly, we can verify that the transition to the steady state ratio of capital to environmental quality is possible in finite time. To analyze the transitional dynamics of the economy, use the necessary conditions and the law of motion of environmental quality to rewrite the system of equations in terms of the rates of growth of consumption and environmental quality. Differentiating λ_t from equation (3.6) with respect to t and setting the result equal to the right hand side of equation (3.7) yields:

$$-\frac{\alpha}{\Pi}\frac{\dot{c}_t}{c_t^2} = \frac{\alpha}{\Pi}\frac{1}{c_t}(\rho-\xi) - \frac{N(1-\alpha)}{E_t}$$

Rearranging:

$$\frac{\dot{c}_t}{c_t} = -(\rho-\xi) + \frac{(1-\alpha)}{\alpha}N\Pi\frac{c_t}{E_t}$$

[2]See appendix D for the derivation of the results.

The rate of growth of environmental quality is:

$$\frac{\dot{E}_t}{E_t} = -P\frac{K_t}{E_t} + \Pi\left(A\frac{K_t}{E_t} - N\frac{c_t}{E_t}\right) + \xi$$

Next, define $\omega_t \equiv \frac{K_t}{E_t}$ and $\chi_t \equiv \frac{c_t}{E_t}$, and rewrite the above as follows:

$$\frac{\dot{c}_t}{c_t} = -(\rho - \xi) + \frac{(1-\alpha)}{\alpha}N\Pi\chi_t$$

$$\frac{\dot{E}_t}{E_t} = -P\omega_t + \Pi\left(A\omega_t - N\chi_t\right) + \xi$$

The rates of growth of ω_t and χ_t are $\frac{\dot{\omega}_t}{\omega_t} = \frac{\dot{K}_t}{K_t} - \frac{\dot{E}_t}{E_t}$ and $\frac{\dot{\chi}_t}{\chi_t} = \frac{\dot{c}_t}{c_t} - \frac{\dot{E}_t}{E_t}$, respectively. Substituting for $\frac{\dot{c}_t}{c_t}$, $\frac{\dot{E}_t}{E_t}$ and $\frac{\dot{K}_t}{K_t}$ yields:

$$\frac{\dot{\omega}_t}{\omega_t} = -\delta + P\omega_t - \Pi A\omega_t + \Pi N\chi_t - \xi$$

$$\frac{\dot{\chi}_t}{\chi_t} = -(\rho - \xi) + \frac{(1-\alpha)}{\alpha}N\Pi\chi_t + P\omega_t - \Pi A\omega_t + \Pi N\chi_t - \xi$$

Rearranging:

$$\dot{\omega}_t = \omega_t\left[-(\delta + \xi) - (\Pi A - P)\omega_t + \Pi N\chi_t\right] \tag{3.8}$$

$$\dot{\chi}_t = \chi_t\left[-\rho - (\Pi A - P)\omega_t + \frac{\Pi N}{\alpha}\chi_t\right] \tag{3.9}$$

The social planner wishes to bring $\omega_0 = \frac{K_0}{E_0}$ down to $\omega^* = \left(\frac{N}{\phi} + \frac{(\varphi-\xi)}{\Pi}\right)\frac{1}{\rho}$ in finite time. To see that this is possible, consider the phase diagram describing (3.8) and (3.9). Figures 3.3, 3.4, and 3.5 depict the three possible cases that are economically relevant (positive quadrant). Rigorously, two loci define an unchanged ω_t (i.e., $\dot{\omega}_t = 0$) in Figures 3.3, 3.4 and 3.5, namely the vertical axis and the line with the largest slope. Similarly, the horizontal axis and the line with the smallest slope define an unchanged χ_t (i.e., $\dot{\chi}_t = 0$). For ease of notation, however, the labels $\dot{\omega}_t = 0$ and $\dot{\chi}_t = 0$ will only refer to the positively sloped curves on the phase diagrams. The curves $\dot{\omega}_t = 0$ and $\dot{\chi}_t = 0$ were obtained by setting the terms in brackets in (3.8) and (3.9) equal to zero:

$$-(\delta+\xi) - (\Pi A - P)\omega_t + \Pi N \chi_t = 0 \;\Rightarrow\; \dot{\omega}_t = 0 \;\Rightarrow\; \chi_t = \frac{(\delta+\xi)}{\Pi N} + \frac{(\Pi A - P)}{\Pi N}\omega_t$$

$$-\rho - (\Pi A - P)\omega_t + \frac{\Pi N}{\alpha}\chi_t = 0 \;\Rightarrow\; \dot{\chi}_t = 0 \;\Rightarrow\; \chi_t = \frac{\alpha\rho}{\Pi N} + \frac{\alpha(\Pi A - P)}{\Pi N}\omega_t$$

From the assumption that $\left(A - \frac{P}{\Pi} - \delta - \rho\right) > 0$, it follows that both loci $\dot{\omega}_t = 0$ and $\dot{\chi}_t = 0$ are positively sloped. Also, since $0 < \alpha < 1$, the locus representing $\dot{\omega}_t = 0$ has a larger slope than the locus representing $\dot{\chi}_t = 0$, as indicated in Figures 3.3, 3.4 and 3.5.

Three relevant fixed points or steady states emerge from inspection of (3.8), (3.9), and Figures 3.3, 3.4 and 3.5. The first fixed point of interest in the ω-χ phase plane is $(0, 0)$, since from (3.8) ω_t is unchanged along the vertical axis, and from (3.9) χ_t is unchanged along the horizontal axis. The second fixed point in the positive quadrant is at the intersection of the line labeled $\dot{\chi}_t = 0$ and the vertical intercept, that is $\left(0, \frac{\alpha\rho}{\Pi N}\right)$. Lastly, the third possible fixed point is at the intersection of $\dot{\omega}_t = 0$ and $\dot{\chi}_t = 0$, that is $\left(\frac{\alpha\rho-\delta-\xi}{(1-\alpha)(\Pi A-P)}, \frac{\alpha(\rho-\delta-\xi)}{(1-\alpha)\Pi N}\right)$.

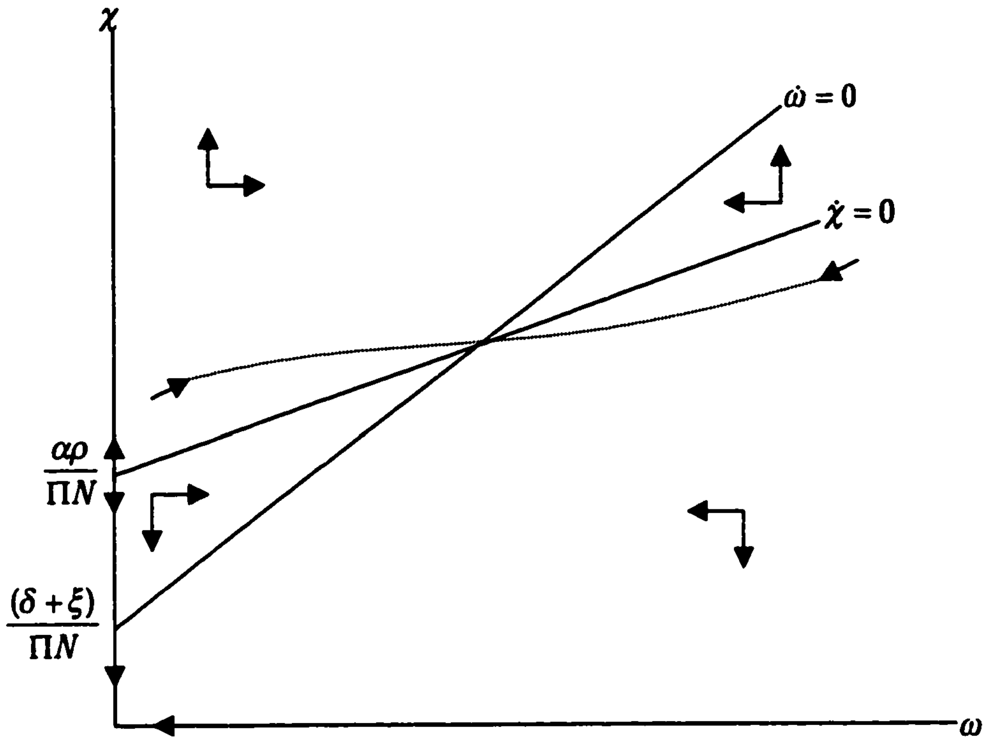


Figure 3.3: Phase Diagram With Abundant Capital Stock: $\alpha\rho > \delta + \xi$.

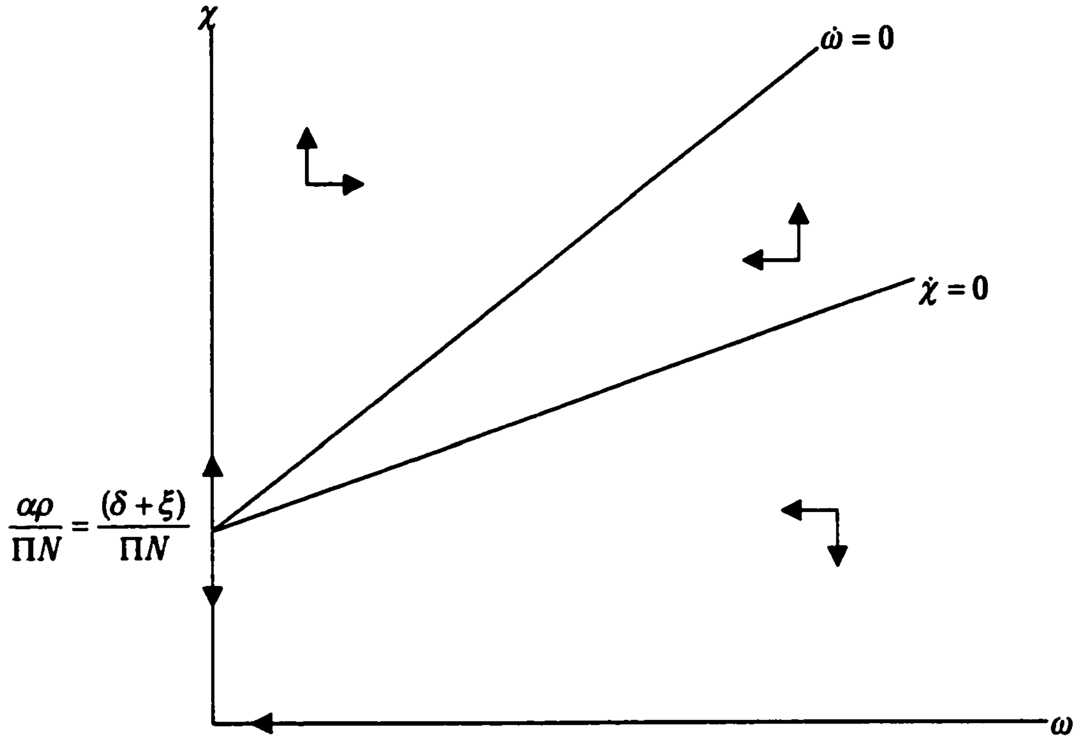


Figure 3.4: Phase Diagram With Abundant Capital Stock: $\alpha\rho = \delta + \xi$.

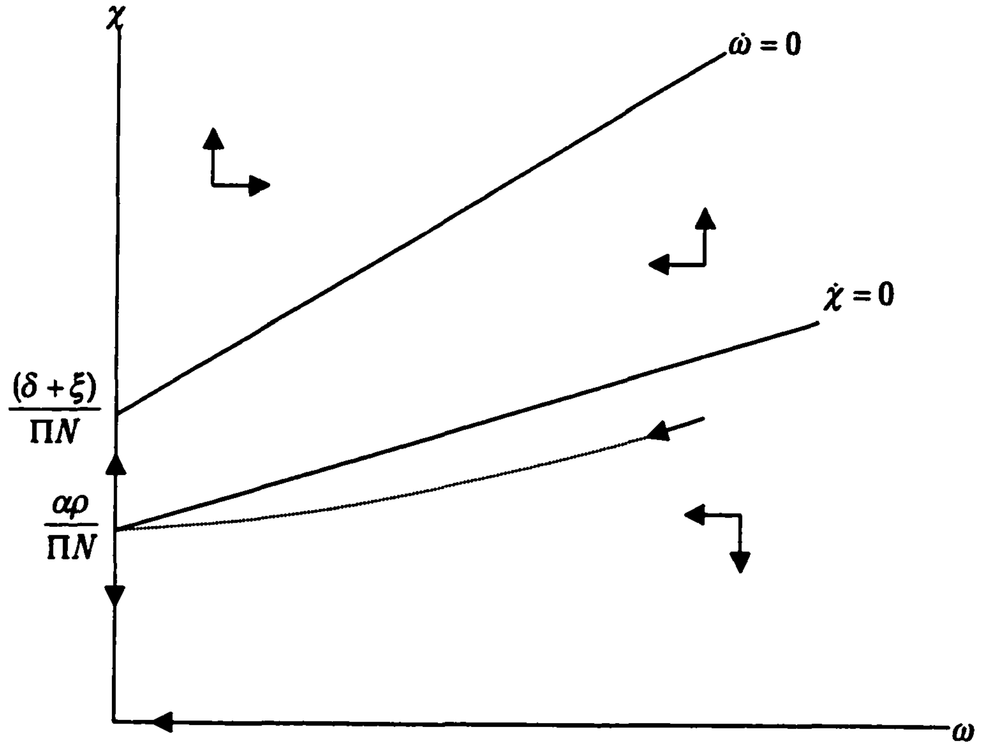


Figure 3.5: Phase Diagram With Abundant Capital Stock: $\alpha\rho < \delta + \xi$.

In order to show that the social planner can reach the desired steady state ratio of capital to environmental quality ω^* in finite time, we need to study the stability of the fixed points of interest. To do that, first linearize (3.8) and (3.9) around the fixed points $(\hat{\omega}, \hat{\chi})$:

$$\dot{\omega}_t = [-(\delta+\xi) - 2(\Pi A - P)\hat{\omega} + \Pi N\hat{\chi}](\omega_t - \hat{\omega}) + \Pi N\hat{\omega}(\chi - \hat{\chi}) + R^{(2)}_{\omega}$$

$$\dot{\chi}_t = -(\Pi A - P)\hat{\chi}(\omega_t - \hat{\omega}) + \left[-\rho - (\Pi A - P)\hat{\omega} + 2\frac{\Pi N}{\alpha}\hat{\chi}\right](\chi_t - \hat{\chi}) + R^{(2)}_{\chi}$$

where $R^{(2)}_{(.)}$ is the remainder of second order of the Taylor expansion, which is negligible in a sufficiently small neighborhood of $(\hat{\omega}, \hat{\chi})$. In a more compact notation:

$$\dot{\omega}_t = a(\omega_t - \hat{\omega}) + b(\chi_t - \hat{\chi}) + R^{(2)}_{\omega} \qquad (3.10)$$

$$\dot{\chi}_t = c(\omega_t - \hat{\omega}) + d(\chi_t - \hat{\chi}) + R^{(2)}_{\chi} \qquad (3.11)$$

The eigenvalues of the system above are given by:

$$\begin{vmatrix} a-\nu & b \\ c & d-\nu \end{vmatrix} = \nu^2 - (a+d)\nu + (ad - bc) = 0$$

$$\nu = \frac{(a+d) \pm \sqrt{(a-d)^2 + 4bc}}{2}$$

The following results help establish the finite time horizon of the transition to the steady state as well as a policy rule to attain the optimal rate of capital to environmental quality. The first result indicates that the origin in the ω-χ phase plane is a local attractor, i.e., it is a locally stable equilibrium, as indicated in Figures 3.3, 3.4 and 3.5.

Lemma 1 *The fixed point* $(0,0)$ *in the* ω-χ *phase plane is locally stable.*

Proof: See appendix E

The next result shows that the equilibrium defined by the intersection of the $\dot{\chi}_t = 0$ locus with the vertical axis of the ω-χ phase plane is locally unstable, as indicated in Figures 3.3, 3.4 and 3.5.

Lemma 2 *The fixed point* $\left(0, \frac{\alpha\rho}{\Pi N}\right)$ *in the* ω-χ *phase plane is locally unstable. Furthermore:*
(i) if $\alpha\rho \geq \delta + \xi$*, then the equilibrium is divergent;*
(ii) if $\alpha\rho < \delta + \xi$*, then the equilibrium exhibits a saddle path behavior.*

Proof: See appendix E

The third result shows that the fixed point given by the intersection of $\dot{\omega}_t = 0$ and $\dot{\chi}_t = 0$ in the positive quadrant (Figure 3.3) exhibits a saddle path behavior.

Lemma 3 *Assume that* $\alpha\rho > \delta + \xi$*, then the fixed point* $\left(\frac{\alpha\rho-\delta-\xi}{(1-\alpha)(\Pi A - P)}, \frac{\alpha(\rho-\delta-\xi)}{(1-\alpha)\Pi N}\right)$ *in the* ω-χ *phase plane is locally unstable and exhibits a saddle path behavior.*

Proof: See appendix E

Finally, we can show that the transition to the steady state ratio of K_t to E_t can be done in finite time. In doing so, the proposition below establishes a policy rule to attain such a goal.

Proposition 2 *For every* $\omega_0 = \frac{K_0}{E_0} > \omega^* = \left(\frac{N}{\phi} + \frac{(\varphi-\xi)}{\Pi}\right)\frac{1}{\rho}$*, there is a* $\chi_0 = \frac{c_0}{E_0}$*, and a time* $t^* < \infty$ *such that the initial conditions* (ω_0, χ_0) *imply* $\omega_{t^*} = \frac{K_{t^*}}{E_{t^*}} = \omega^* = \left(\frac{N}{\phi} + \frac{(\varphi-\xi)}{\Pi}\right)\frac{1}{\rho}$.

Discussion: Consider the cases described by lemma 3 and lemma 2 (ii). They correspond to Figures 3.3 and 3.5, respectively. In both cases, the dashed line represents the positively sloped convergent separatrix (or stable arm) of the equilibrium of interest. In order to complete the transition to the steady state ratio of capital to environmental quality (ω^*), for any $\omega_0 < \omega^*$, it suffices for the social planner to choose χ_0 such that the initial point in the phase plane is below the stable arm. This will result in both ω_t and χ_t approaching zero as time goes to infinity. Consequently, there is a finite time t^* such that $\omega^* = \left(\frac{N}{\phi} + \frac{(\varphi-\xi)}{\Pi}\right)\frac{1}{\rho}$. Similarly, for the case described by lemma 2 (i), when $\alpha\rho = (\delta + \xi)$, it suffices for the social planner to pick $\chi_0 < \frac{\alpha\rho}{\Pi N}$ and ω_t will go to zero as time goes to infinity.

Proof:

Case (i): $\alpha\rho > (\delta + \xi)$ or $\alpha\rho < (\delta + \xi)$.

From lemma 2 (ii) the fixed point $\left(0, \frac{\alpha\rho}{\Pi N}\right)$ exhibits a saddle path behavior. Likewise, lemma 3 shows that the fixed point $\left(\frac{\alpha\rho-\delta-\xi}{(1-\alpha)(\Pi A-P)}, \frac{\alpha(\rho-\delta-\xi)}{(1-\alpha)\Pi N}\right)$ exhibits a saddle path behavior. In both cases, first define the convergent separatrix $\chi = S_s(\omega)$ as indicated in Figures 3.3 and 3.5. In the neighborhood of ω_0, pick χ_0 such that $S_s(\omega_0) - \chi_0 > 0$. Then, from lemma 1 and the directions of movement of ω_t and χ_t from Figures 3.3 and 3.5, it follows that $\lim_{t\to\infty} \omega_t = 0$. Consequently, there is a time $t^* < \infty$ such that $\omega_0 > \omega_{t^*} = \left(\frac{N}{\phi} + \frac{(\varphi-\xi)}{\Pi}\right)\frac{1}{\rho} > 0$.

Case (ii): $\alpha\rho = (\delta + \xi)$.

From lemma 2 (i) the fixed point $\left(0, \frac{\alpha\rho}{\Pi N}\right)$ is divergent. Given ω_0, in order to reach ω^* in finite time it suffices to pick χ_0 such that $\chi_0 < \frac{\alpha\rho}{\Pi N}$. According to lemma 1 and the directions of movement of ω_t and χ_t from Figure 3.4, it follows that $\lim_{t\to\infty} \omega_t = 0$. Consequently, there is a time $t^* < \infty$ such that $\omega_0 > \omega_{t^*} = \left(\frac{N}{\phi} + \frac{(\varphi-\xi)}{\Pi}\right)\frac{1}{\rho} > 0$. ■

Proposition 2 defines a sufficient but not necessary policy rule for the social planner to reach the steady state ratio of capital to environmental quality in finite time. To see that this is true, suppose that in Figures 3.3, 3.4 and 3.5, the steady state ratio of capital to environmental quality ω^* is to the right of the intersection of $\dot{\omega}_t = 0$ and $\dot{\chi}_t = 0$. Then, given $\omega_0 > \omega^*$, any χ_0 above the dashed line and below $\dot{\omega}_t = 0$ in Figures 3.3 and 3.5 will produce a decreasing ω_t in a finite time interval. Therefore, it may be the case that ω^* is reached in finite time. A similar comment applies to χ_0 between $\dot{\chi}_t = 0$ and $\dot{\omega}_t = 0$ in Figure 3.4.

Also notice that given $\omega_0 > \omega^*$, the policy rule resulting from proposition 2 does not specify a unique χ_0 consistent with the optimal steady state ratio of capital to environmental quality. This may help account for the diversified environmental protection policies in the transition economies.

3.5 CONCLUSION

This chapter provides a theoretical framework for the economic analysis of environmental quality in transition economies. The model relies on evidence on environmental quality and economic performance of countries of the former Soviet bloc and poses the conjecture that those nations over invested in capital accumulation relative to environmental protection.

The optimal path of environmental quality for economies with a large capital stock relative to environmental quality was then derived. The results of the simplified model are consistent with depressed economic activity in the transition economies and the diversity of policies to improve environmental quality in both CEE countries and the NIS. In particular, a policy rule consistent with attainment of the optimal ratio of capital to environmental quality in finite time was derived.

Chapter 4

ENVIRONMENTAL QUALITY, ENVIRONMENTAL PROTECTION AND TECHNOLOGY ADOPTION

4.1 INTRODUCTION

This chapter investigates how barriers to technology adoption affect environmental quality in different countries. More specifically, this chapter shows how different technologies contribute to a U-shaped relationship between environmental quality and income in cross-sections of countries. This relationship is implied by the environmental Kuznets curve (EKC), an inverted U-shaped relationship between pollution and income. We conduct the analysis by focusing on Pareto optimality in the steady state of a dynamic economy where different technologies are considered.

A number of studies investigate empirical patterns of pollution (and implied environmental quality) at different levels of income. In cases where pollution control is technically and institutionally feasible, the EKC indicates that emissions tend to rise with income up to a point where they start to decline (see for example, Shafik and Bandyopadhyay, 1992, Grossman and Krueger, 1995, and Selden and Song, 1994). The EKC is often interpreted as a by-product of economic growth, implying that the decline and subsequent recovery of environmental quality is a matter of time reflecting the natural path of economic development. For example, Grossman and Krueger (1995, p. 372) state that "air and water quality appear to benefit from economic growth once some critical level of income has been reached." In a similar empirical paper, Selden and Song (1994, p. 147) write that "it is reasonable to expect that economies would pass through 'stages of development', in which at least some aspects of environmental quality first deteriorate and then improve." However, since time series on pollution and environmental quality are generally short and variable in quality, evidence on the relationship between environmental quality and economic development heavily relies on cross-sectional data for different countries. The use of cross-sectional data raises the question of whether country-specific characteristics matter when explaining the EKC. If this is the case, as this chapter suggests, the time-series interpretation bears an extra burden of proof, since it assumes that countries are identical and follow a predetermined path for environmental quality.

Most empirical studies on development and the environment use panel data analysis. For example, Grossman and Krueger (1995) and Selden and Song (1994) use panel data to investigate how pollution responds to income, and they find an inverted-U relationship between these variables. With panel data analysis, the effect of country specific characteristics can be explored by estimating within or random effects models. However, in the case where the country specific characteristics are correlated with income (the usual measure for economic development), the estimates of the relationship between environmental quality and economic development are subject to bias and inconsistency (Hausman and Taylor, 1981). This chapter provides theoretical support to these qualifications by considering barriers to technology adoption in different countries.

Barriers to technology adoption constitute an important factor that is believed to account for much of the variation in income across countries (Parente and Prescott, 1994 and 2000). This chapter investigates the effect of these barriers on the environment and their contribution to the empirical relationship between development and environmental quality. It does so by performing comparative statics on the steady state of a dynamic economy where the society's total factor productivity (TFP) is allowed to change. Heterogeneous TFPs across countries correspond to different multiplicative technological parameters of their aggregate production functions (Parente and Prescott, 2000). Furthermore, the model presented here enables investigation of the effect of barriers to technology adoption in two other aggregate technical relationships: (i) the aggregate environmental protection function interpreted as end-of-the-pipe environmental clean-up; and (ii) the aggregate pollution function, assumed to depend on the stock of capital of the economy.

4.2 RELATED LITERATURE

After the initial studies highlighting the EKC in the early 1990s, several scholars have tried to provide a theoretical explanation for the phenomenon, mostly considering the dynamic nature of pollution (and environmental quality). In a simple dynamic model, Selden and Song (1995) derived conditions for the EKC that are sufficient but not necessary. John and Pecchenino (1994) and Jones and Manuelli (1994) used overlapping generations models where the young choose a tax scheme that accounts for environmental quality when they are old. In a more recent paper, Stokey (1998) developed a dynamic model where the EKC is consistent with Pareto optimality, although the result depends on the rather restrictive assumption that more efficient technologies are necessarily more pollution intensive. In a different context, Reppelin-Hill (1999) analyzed the case where a more efficient technology is less pollution intensive. Two static models consistent with the EKC appear in Andreoni and Levinson (1998) and Stokey (1998).

These studies fail to recognize that an important cause of the great differences in national incomes is heterogeneity in their total factors of productivity (TFPs) as pointed out by Parente and Prescott (1994). The difference in TFPs originates from a nation's institutional environment, such as regulatory and legal constraints, cultural values, corruption, violence, sabotage, and worker strikes (Parente and Prescott, 1994). These institutional factors help determine the optimal stock of capital, environmental quality and aggregate output in each country and are essential in the analysis of the relationship between environmental quality and income, especially when most empirical evidence on this relationship relies on cross-country observations. For example, large barriers to technology adoption reduce capital productivity, thus leading to a smaller capital stock, aggregate output and pollution. In this scenario, the shadow value of capital is likely to exceed that of environmental quality. A reduction in barriers to technology adoption permits more capital utilization and pollution. As barriers to technology adoption are further reduced, increased capital accumulation and wealth cause the shadow values to equalize. Further growth will enable both further capital accumulation and increasing environmental protection.

In addition to explaining the effect of differences in TFPs, this chapter analyzes the effect of heterogeneity in technical parameters of the aggregate environmental protection and pollution functions of different nations. The differences in these technical parameters also originate from the institutional environment and have an impact on environmental quality, environmental expenditures, consumption and capital accumulation.

4.3 MODEL

Consider a dynamic model with environmental quality treated as a stock variable. That is, environmental quality in any time period depends on cummulative pollution and environmental protection. Leading examples of environmental phenomena best characterized as stocks include depletion of the ozone layer, the greenhouse effect, and deforestation and biodiversity loss.

In the dynamic model presented here, the social planner maximizes the stream of social welfare over an infinite time horizon. Each individual in society values consumption per capita (c_t) and the stock of environmental quality (E_t) at each time t. Welfare is defined as the summation of the utility functions $u(c_t, E_t)$ of N representative individuals and its maximization is constrained by the laws of motion for the stock of capital (K_t) and environmental quality (E_t). Capital accumulation results from the difference between total production ($F(K_t)$, a concave function of capital) and aggregate expenditure on consumption (Nc_t) and environmental preservation effort (π_t), both measured in units of output. For simplicity, assume zero capital depreciation. Environmental quality on the other hand decreases with the stock of capital (pollution function, $P(K_t)$) and increases with effort on environmental protection (environmental improvements function, $\Pi(\pi_t)$). The problem is formally described as follows:

$$\max_{c_t,\pi_t} \int_0^\infty e^{-\rho t} N u(c_t, E_t) dt$$

subject to:

$\dot{E}_t = -P(K_t) + \Pi(\pi_t)$, $\dot{K}_t = F(K_t) - Nc_t - \pi_t$, $E_t \geq 0$, $K_t \geq 0$,

$c_t \geq 0$, $\pi_t \geq 0$, and initial conditions E_0 , K_0,

where ρ is the real discount rate ($\rho > 0$). Also, assume that:

$u_c > 0$; $u_{cc} < 0$; $u_E > 0$; $u_{EE} < 0$; $u_{cE} \geq 0$; $\lim_{c \to 0} u_c = \infty$; $\lim_{E \to 0} u_E = \infty$,

$P_K > 0$; $P_{KK} > 0$; $\lim_{K \to 0} P_K = 0$; $\lim_{K \to \infty} P_K = \infty$,

$F_K > 0$; $F_{KK} < 0$; $\lim_{K \to 0} F_K = \infty$; $\lim_{K \to \infty} F_K = 0$,

$\Pi_\pi > 0$; $\Pi_{\pi\pi} \leq 0$; $\lim_{\pi \to 0} \Pi_\pi = \infty$; $\lim_{\pi \to \infty} \Pi_\pi = 0$.

4.3.1 Optimality

The current value Hamiltonian for an interior solution is given by:

$$H = Nu(c_t, E_t) + \lambda_t[-P(K_t) + \Pi(\pi_t)] + \mu_t[F(K_t) - Nc_t - \pi_t].$$

The necessary conditions for the above problem are:

$$\partial H / \partial c_t = Nu_c - N\mu_t = 0 \;\; \Rightarrow \;\; \mu_t = u_c,$$

$$\partial H / \partial \pi_t = \lambda \Pi_\pi - \mu_t = 0 \;\; \Rightarrow \;\; \lambda_t = \frac{\mu_t}{\Pi_\pi},$$

$$\dot{\lambda}_t = \rho \lambda_t - N u_E,$$

$$\dot{\mu}_t = \rho\mu_t - [-\lambda_t P_K + \mu_t F_K].$$

Manipulation of the necessary conditions yields:

$$\dot{c}_t = \frac{u_c}{u_{cc}}\left(\frac{P_K}{\Pi_\pi} - F_K + \rho - \frac{u_{cE}}{u_c}\dot{E}_t\right), \tag{4.1}$$

$$\dot{\pi}_t = \frac{\Pi_\pi}{\Pi_{\pi\pi}}\left(\frac{u_{cc}\dot{c}_t + u_{cE}\dot{E}_t}{u_c} - \rho + N\frac{u_E}{u_c}\Pi_\pi\right). \tag{4.2}$$

Along the optimal consumption path given by equation (4.1), a larger marginal contribution of capital to pollution or smaller productivity of capital reduces the rate of increase in consumption. Also, increasing environmental quality over time ($\dot{E}_t > 0$) accelerates consumption growth. Similarly, barriers to technology adoption that make preservation effort less productive (decrease Π_π) contribute to slower consumption growth.

Suppose the economy is growing. Equation (4.2) indicates that, *ceteris paribus*, if consumption *per capita* is increasing, so is preservation effort in order to compensate for a more degraded environment due to increasing use of capital. Similarly, if environmental quality is decreasing over time, preservation effort will grow faster to keep the discounted stream of utility at a maximum. Also, growth of preservation effort over time is decreasing in the discount rate and increasing in the marginal rate of substitution of environmental quality for consumption and marginal environmental improvement from environmental expenditures π_t.

4.3.2 Steady State

Important insight can be obtained by studying the steady state of this dynamic economy. The motivation for focusing on the steady state is twofold: It simplifies the analysis and, most importantly, it allows us to focus on the underlying economic forces of interest. For simplicity, we assume a constant elasticity utility function. For $\sigma, \beta, \varphi, \psi > 0$, and $0 < \delta \leq 1$, define the utility and environmental protection functions as follows:

$$u(c_t, E_t) = \varphi \frac{c_t^{1-\sigma} - 1}{1-\sigma} + \psi \frac{E_t^{1-\beta} - 1}{1-\beta},$$

$$\Pi(\pi_t) = \Pi \pi_t^{\delta}.$$

Then, rewrite equations (4.1) and (4.2) in terms of the rates of growth of consumption (γ_c) and environmental protection effort (γ_π). Economic growth in this economy is described by these two rates of growth plus rates of change in capital stock (γ_K) and environmental quality (γ_E):

$$\gamma_c \equiv \frac{\dot{c}_t}{c_t} = -\frac{1}{\sigma}\left(\frac{P_K}{\Pi_\pi} - F_K + \rho\right),$$

$$\gamma_\pi \equiv \frac{\dot{\pi}_t}{\pi_t} = \frac{1}{(\delta - 1)}\left(\gamma_c - \rho + N\frac{u_E}{u_c}\Pi_\pi\right),$$

$$\gamma_E \equiv \frac{\dot{E}_t}{E_t} = \frac{-P(K_t) + \Pi(\pi_t)}{E_t},$$

$$\gamma_K \equiv \frac{\dot{K}_t}{K_t} = \frac{F(K_t) - Nc_t - \pi_t}{K_t}.$$

The steady state is defined as the state where all variables grow at a constant rate. This implies that the growth rates for the variables of the model are equal tc zero in the steady state:

Proposition 3 *In the steady state, the rates of growth of consumption (γ_c), environmental expenditures (γ_π), the stock of capital (γ_K) and environmental quality (γ_E) are equal to zero.*

Proof: See appendix F.

Hence, optimality in the steady state reduces to:

$$\frac{P_K}{\Pi_\pi} - F_K + \rho = 0, \tag{4.3}$$

$$Nu_E \Pi_\pi - u_c \rho = 0, \tag{4.4}$$

$$-P(K_t) + \Pi(\pi_t) = 0, \tag{4.5}$$

$$F(K_t) - Nc_t - \pi_t = 0. \tag{4.6}$$

Rearranging equation (4.4) yields the dynamic Samuelson condition for the provision of environmental quality:

$$N\frac{u_E}{u_c}\frac{1}{\rho} = \frac{1}{\Pi_\pi}.$$

That is, the discounted sum of the marginal rates of substitution of environmental quality for consumption across all individuals must equal the marginal cost of provision of environmental quality (units of output spent per unit of additional environmental quality).

Similarly, equation (4.3) indicates optimality in the production sector of the economy, i.e., the optimal trade-off between the marginal social benefit of capital and its marginal social cost. The marginal product of capital must equal the discount rate plus the cost of foregone environmental quality due to additional capital use. Clearly, given the concavity assumption on the production function $F(K_t)$, optimality with polluting capital implies a smaller steady state capital stock than otherwise:

$$F_K = \rho + \frac{P_K}{\Pi_\pi}.$$

4.3.3 Effect of Technology Adoption on Economic Variables

This section analyzes the effect of technological differences on the steady state of the model. We assume that this heterogeneity is due to barriers to technology adoption. Barriers to technology adoption are assumed to translate into higher costs for firms to adopt a new and higher quality technology. Parente and Prescott (2000) show how these costs affect the TFP and consequently not only the market equilibrium, but also the Pareto optimal allocations. This chapter focuses on Pareto optimality and extends the concept of total factor productivity from the aggregate production function to the aggregate environmental protection and the pollution functions. For example, stringency and enforcement of national environmental regulation will provide incentives for the adoption of more efficient environmental protection technologies such as abatement technologies, thus increasing marginal efficiency of environmental protection effort (Π_π). At the same time it will provide incentives for the adoption of less pollution intensive technologies, thus decreasing marginal pollution of capital (P_K). For simplicity, the analysis presented here abstracts from interactions between these barriers to technology adoption and treats the final effect on the parameters of the aggregate production, pollution and environmental protection functions as independent.

Without loss of generality, normalize population so that $N = 1$. Next, assume that the production function ($F(K_t)$), the pollution function ($P(K_t)$) and the environmental protection function ($\Pi(\pi_t)$) are as follows:

$$F(K_t) = A \cdot F^\circ(K_t) \;\; ; \;\; P(K_t) = B \cdot P^\circ(K_t) \;\; ; \;\; \Pi(\pi_t) = D \cdot \Pi^\circ(\pi_t),$$

where A, B and D are the aggregate technological parameters that vary across countries and, according to our assumptions in section 4.3, $F_K^o > 0$, $F_{KK}^o < 0$, $P_K^o > 0$, $P_{KK}^o > 0$, $\Pi_\pi^o > 0$ and $\Pi_{\pi\pi}^o \leq 0$. More efficient technologies correspond to larger parameters A and D in the aggregate production and environmental protection functions, and smaller parameter B in the pollution function. Following Parente and Prescott (1994 and 2000), thc institutional environment of a country influences the cost of adopting a new technology of production, environmental protection and pollution prevention. For example, lax environmental regulations decrease the private opportunity cost of using pollution intensive technologies, implying a larger parameter B in the aggregate pollution function. Likewise, excessive bureaucracy increases the cost of environmental protection, making the parameter D in the aggregate environmental protection function smaller. In what follows, we focus on Pareto optimality given the aggregate technological parameters A, B and D of the economy.

The effect of barriers to technology adoption will depend on the type of technological heterogeneity (in the production function, the environmental protection function or in the pollution function) and the specific steady state of the economy. Comparative statics on the steady state will give the direction of the effect of technological differences on the variables of interest. Table 4.1 presents the resulting derivatives of the comparative statics for linear and strictly concave forms of the environmental protection function. The derivation of the more general results with $\Pi_{\pi\pi} \leq 0$ appears in appendix G.

From Table 4.1, we see that when environmental protection is linear, reducing barriers to technology adoption leading to improved aggregate efficiency will always improve environmental quality[1]. With respect to the environmental Kuznets curve, the middle row of the

[1]Improved technological efficiency in the pollution function $P(K_t)$ corresponds to lower values of the technical parameter B.

Table 4.1: Effect of Technology Adoption on c, E, π and K

Sign of Derivative	Linear $\Pi(\pi)$	Concave $\Pi(\pi)$
>0	$\frac{dc}{dA}, \frac{d\pi}{dA}, \frac{dE}{dA}, \frac{dK}{dA}, \frac{dc}{dD}, \frac{dE}{dD}, \frac{dK}{dD}$	$\frac{dc}{dA}, \frac{d\pi}{dA}, \frac{dK}{dA}, \frac{dc}{dD}, \frac{dE}{dD}, \frac{dK}{dD}$
$\gtrless 0$	$\frac{d\pi}{dD}, \frac{d\pi}{dB}$	$\frac{dE}{dA}, \frac{d\pi}{dD}, \frac{d\pi}{dB}, \frac{dE}{dB}$
<0	$\frac{dc}{dB}, \frac{dE}{dB}, \frac{dK}{dB}$	$\frac{dc}{dB}, \frac{dK}{dB}$

third column indicates that the possibility for a U-shaped curve for environmental quality will only exist for heterogeneity in TFPs (A) or pollution intensity of capital (B) when the environmental protection function $\Pi(\pi_t)$ is assumed to be strictly concave, thus exhibiting aggregate decreasing returns. To gain more insight into the conditions for an EKC as income varies, we focus on differences of the TFPs across countries (parameter A) due to its relative importance to national income (Parente and Prescott, 1994). The sign of the derivative of environmental quality with respect to the technical parameter A will depend on the curvature of the utility and the environmental protection functions at each steady state, reflecting the relative importance of capital and environmental quality in determining the optimal response of consumption and environmental expenditures to changes in TFPs. Proposition 4 summarizes this result.

Proposition 4 *The derivative of environmental quality with respect to the total factor productivity (TFP) depends on the curvature of the utility and environmental protection functions as follows:* $\frac{dE}{dA} \gtrless 0$ *if and only if* $\frac{\Pi_{\pi\pi}}{\Pi_\pi}\frac{d\pi}{dA} \gtrless \left(\frac{u_{cc}}{u_c} - \frac{u_{Ec}}{u_E}\right)\frac{dc}{dA}$.

Proof: See appendix H.

For simplicity and in order to obtain further insight into the EKC, we specialize to constant elasticity utility and a simple strictly concave environmental protection function. The EKC will depend on the elasticity of intertemporal substitution of consumption, the degree of concavity of the environmental protection function, and the elasticities of consumption and environmental expenditures with respect to the total factor productivity (parameter A):

Corollary 1 *Define the utility function as* $u(c_t, E_t) = \varphi\frac{c_t^{1-\sigma}-1}{1-\sigma}+\psi\frac{E_t^{1-\beta}-1}{1-\beta}$, *where* $\sigma, \beta, \varphi, \psi > 0$, *and the environmental protection function as* $D\Pi^{\circ}(\pi_t) = D\pi_t^{\delta}$, *where* $0 < \delta < 1$. *Then,*

$$\frac{dE}{dA} \gtrless 0 \quad \textit{if and only if} \quad \sigma\eta_c^A \gtrless (1-\delta)\eta_\pi^A,$$

where $\eta_c^A = \frac{dc}{dA}\frac{A}{c}$ *and* $\eta_\pi^A = \frac{d\pi}{dA}\frac{A}{\pi}$ *are the elasticities of consumption and environmental expenditures with respect to the total factor productivity.*

Proof: See appendix H.

From corollary 1, it follows that as δ approaches 1, the term $(1-\delta)\eta_\pi^A$ approaches zero. Consequently, since the term $\sigma\eta_c^A = \sigma\frac{dc}{dA}\frac{A}{c}$ is strictly positive (Table 4.1), environmental quality will increase with increases in productivity (parameter A). In the limiting case ($\delta = 1$), environmental protection is linear in environmental protection effort and environmental quality is always increasing with increases in A, as shown in Table 4.1.

The analytical results presented in Table 4.1 indicate that, with the exception of consumption and the stock of capital, the effect of technological improvements (larger A or D, and smaller B) due to smaller institutional barriers is ambiguous. Therefore, there is potential insight to be obtained from numerical analysis of the comparative statics of the model. We perform comparative statics in the steady state of the dynamic model in the next section.

4.4 NUMERICAL ANALYSIS

This section reports numerical comparative statics of the steady state of the model with the following functional forms[2]:

$$u(c_t, E_t) = \alpha \ln(c_t) + (1-\alpha)\ln(E_t),$$

$$B \cdot P^{\circ}(K_t) = BK_t^b,$$

$$D \cdot \Pi^{\circ}(\pi_t) = D\pi_t^{\delta},$$

$$A \cdot F^{\circ}(K_t) = AK_t^m.$$

With $0 < \alpha < 1$, $b \geq 1$, $0 \leq \delta \leq 1$, and $0 \leq m \leq 1$. More specifically, the baseline parameters are $\alpha = 0.8$, $b = 1.5$, $\delta = 0.15$, $m = 0.35$ and $\rho = 0.02$.

Due to the difficulty in obtaining aggregate data for the pollution function $B \cdot P(K_t)$ and the environmental protection function $D \cdot \Pi(\pi_t)$, no attempt was made to calibrate the model to real world circumstances. Instead, we use consolidated parameters in the literature when they are available and focus on the qualitative results of the numerical analysis. The value for the parameter m corresponds to the share of capital in the production function in the U.S.

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[2]Notice that the utility function used here is obtained from $u(c_t, E_t) = \varphi\frac{c_t^{1-\sigma}-1}{1-\sigma} + \psi\frac{E_t^{1-\beta}-1}{1-\beta}$ from Section 4.3.3 by letting $\sigma, \beta \to 1$, $0 < \varphi = \alpha < 1$, and $\psi = (1-\alpha)$. Maximizing the logarithmic case of the utility function is convenient since this is equivalent to maximizing the Cobb-Douglas case $u(c_t, E_t) = c_t^{\alpha} E_t^{(1-\alpha)}$. In the Cobb-Douglas formulation, $u_{cE} > 0$, reproducing the intuitive notion that higher environmental quality (E_t) makes consumption (c_t) more enjoyable.

of approximately 1/3. The real discount factor $\rho = 0.02$ and the intertemporal elasticity of substitution $1/\sigma = 1$ are also typically used in the literature (see for example Cooley, 1995, and Barro and Sala-i-Martin, 1995). The choice of α, b and δ is arbitrary since little empirical information on these parameters is available. The value $\alpha = 0.8$ represents the relative importance of consumption compared to environmental quality. The values $b = 1.5$ and $\delta = 0.15$ produce a convex pollution function and concave environmental protection function respectively. Because of the importance of the parameters δ and σ to the U-shaped curve for environmental quality as shown in corollary (1), other combinations are considered below. For ease of manipulation, the initial values of the technological parameters A, B and D are set equal to 10. Finally, the functional forms specified here conform to the assumptions in section 4.3.

Based on the preceding parameter values, a real-valued steady state solution is given by $c^* = 9.289$, $\pi^* = 0.335$, $K^* = 0.896$, and $E^* = 441.196$. We can verify that these values represent an equilibrium with saddle stability[3]. The economic interpretation here is the usual one for equilibria presenting saddle stability. Since this is a deterministic model of the economy and we assume the social planner is fully rational, there is no reason to deviate from the optimal path to the steady state given the initial conditions of the state variables. We assume implicitly that the optimal path is feasible given the initial conditions[4].

[3]To check for stability of the steady state, we linearize the system of differential equations describing optimality for c_t, π_t, E_t and K_t and calculate the eigenvalues of the resulting Jacobian matrix. Refer to Appendix I.

[4]To guarantee feasibility, we can assume that the pristine level of the environment is large enough to assure the necessary initial stock of capital, and the resulting consumption and environmental preservation effort. That is, assume an extractive economy at time zero with enough resources to take the state and control variables to a stable path to the steady state. Clearly, this hypothesis is sufficient but not necessary to produce a feasible optimal path.

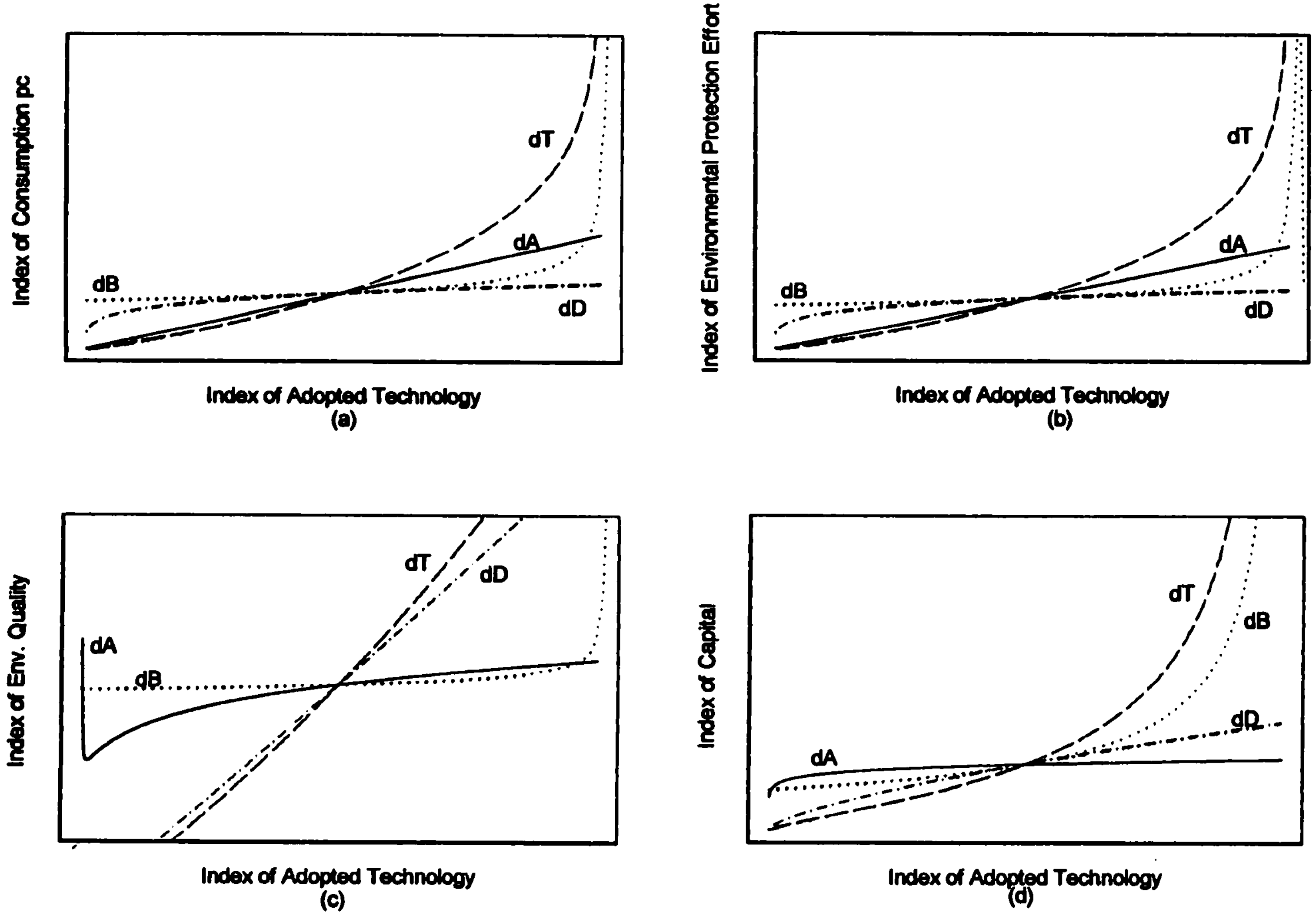

Figure 4.1: Technology Adoption, Consumption, Preservation Effort, Environmental Quality and Capital.

Figure 4.1 shows the response of consumption per capita, environmental protection effort, environmental quality and capital stock to differences in each of the technological parameters in the steady state. Recall that each point in Figure 4.1 corresponds to a different steady state obtained by a different set of parameters, in accordance with the use of comparative statics to describe different countries. Adoption of more efficient technologies corresponds to movement to the right along the horizontal axis. Thus, by construction, movement to the right along the horizontal axis corresponds to increasing A (total productivity of capital) and D (total environmental protection efficiency), and decreasing B (total pollution intensity of capital). The vertical axis measures the effect of adopting different technologies on the economic variables of interest. The curves labeled "dT" show the combined effect of simultaneous changes in A, B and D, whereas "dA", "dB" and "dD" indicate the separate responses of the economic variables to more productive capital, less pollution intensive capital and more efficient preservation effort. The points where the lines cross on each of the graphs in Figure 4.1 are nothing but the baseline points for the numerical simulation, where A, B and D all equal 10.

4.4.1 Effect of Technology Adoption on Economic Variables

We focus first on the effect of different TFPs (curves labeled "dA") on the variables of the model. Higher values of the TFPs correspond to increasing consumption (figure 4.1(a)), environmental protection effort (figure 4.1(b)) and capital stock (figure 4.1(d)) in the steady state. More interestingly, the response of environmental quality to more productive capital is not monotone (figure 4.1(c)). Starting with small TFPs, marginal increases of this parameter cause environmental quality in the steady state to fall. The trend is eventually reversed and environmental quality rebounds. Thus, in a cross-section of countries, if we start with a country with a small TFP and income (large barriers to technology adoption) and compare it to another with a marginally larger TFP and income (marginally smaller barriers to technology adoption), the increased TFP will result in less environmental quality. This trend is eventually reversed as we look at richer countries with substantially larger TFPs (smaller barriers to technology adoption). This is consistent with Pareto optimality and the environmental Kuznets curve.

The effect of different TFPs on environmental quality follows from the system of equations (4.3) through (4.6), describing the steady state of the economy, together with the result in corollary 1. Equations (4.3) through (4.6) form a block recursive system. In particular. we can use equations (4.3), (4.5) and (4.6) to solve for c^*, a^* and K^* as functions of the parameters of the model. Then, equation (4.4),

$$Nu_E\Pi_\pi - u_c\rho = 0,$$

provides necessary and sufficient conditions for the determination of environmental quality consistent with optimality. Therefore, from equation (4.6),

$$F(K_t) - Nc_t - \pi_t = 0,$$

as the parameter A (TFP) approaches zero, so does production $F(K_t)$ and consequently consumption c_t and preservation effort π_t. From corollary 1, for a sufficiently small value of parameter δ of the environmental protection function, marginal environmental protection

(Π_π) goes to infinity faster than marginal utility (u_c). From equation (4.4), for optimality to result, the marginal utility of environmental quality has to be small, thus the high value of E_t. In other words, optimality requires that smaller consumption be offset by higher environmental quality. With sufficiently small consumption, the shadow value of capital is high relative to the shadow value of the environment. Therefore, smaller barriers to adoption of technologies that increase capital productivity favor an increase in the capital stock and a decrease of environmental quality. As we move to higher TFPs, however, production eventually increases to afford both more consumption and environmental protection, and environmental quality rebounds. This path is depicted by the curve "dA" in Figure 4.1(c).

As corollary 1 indicates, the shape of the curve for environmental quality depends crucially on the concavity of the environmental protection function. Figure 4.2 presents some alternative values of δ and σ that are consistent with a U-shaped relationship of environmental quality to total factor productivity.

The numerical results in Figure 4.1 indicate that more efficient environmental protection (curves labeled "dD") corresponds to increasing consumption (figure 4.1(a)), environmental protection effort (figure 4.1(c)) and capital (figure 4.1(d)). The same is true for the adoption of technologies that make capital less pollution intensive (curves labeled "dB"), except for the response of environmental protection effort. Figure 4.1(b) shows how cleaner capital causes environmental protection effort to decline. The intuition behind this result is available from equation (4.5),

$$-P(K_t) + \Pi(\pi_t) = 0,$$

describing constant environmental quality in the steady state. Cleaner capital corresponds to smaller parameter B and consequently less pollution $P(K_t)$ per unit of capital. As B and $P(K_t)$ go to zero, equation (4.5) requires that preservation effort and aggregate environmental preservation also go to zero so as to keep environmental quality constant in the steady state. This explains the decrease in environmental protection effort in Figure 4.1(b).

The curves labeled "dT" show that the combined effect of smaller barriers to adoption of efficiency augmenting technology in aggregate production, aggregate pollution and aggregate environmental protection is to increase consumption (figure 4.1(a)), environmental protection effort[5] (figure 4.1(b)), environmental quality (figure 4.1(c)) and capital (figure 4.1(d)).

Under the conditions in corollary 1, Figure 4.1 indicates that smaller barriers to technology adoption promote increased consumption, environmental expenditures and stock of capital. The same is true for environmental quality, except for differences in TFPs (parameter A), which delineate a curve that is decreasing for larger barriers to technology adoption (lower TFPs) and increasing for smaller barriers to technology adoption (higher TFPs). This result is consistent with the cross-sectional evidence on the EKC reported in the literature.

[5]More precisely, environmental protection effort initially increases, but eventually decreases as B alone falls to zero. This drop in environmental protection effort is not shown in Figure 4.1(b) to limit the scale of the vertical axis and allow meaningful comparisons of the curves of the graph.

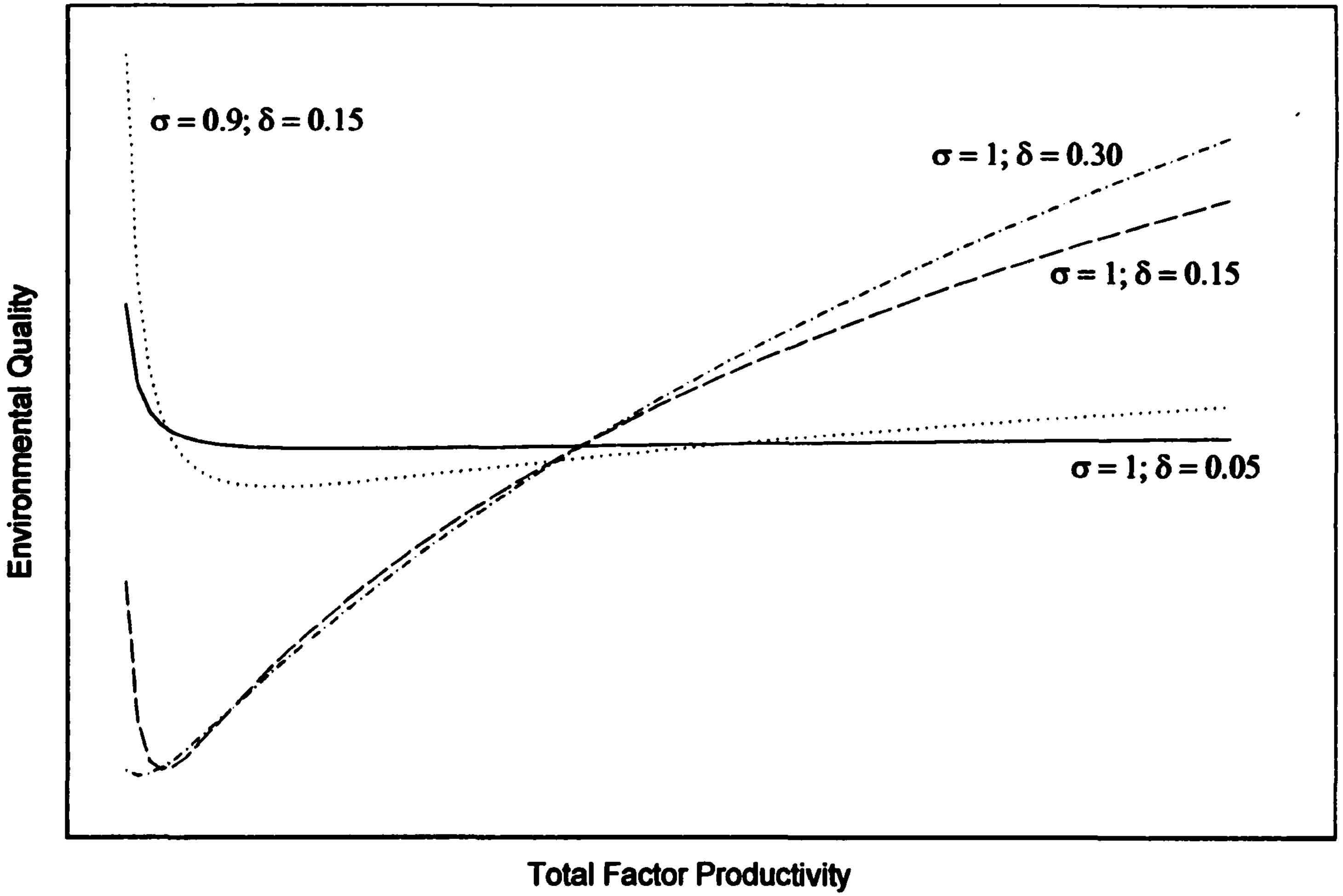

Figure 4.2: Total Factor Productivity and Environmental Quality.

4.5 CONCLUSION

This chapter develops a dynamic model relating technology adoption and environmental quality. It shows how country-specific characteristics can help explain the existence of the environmental Kuznets curve. In particular, differences in total factor productivity can produce the U-shaped relationship of environmental quality and income depending on the shadow values of capital and environmental quality. An implication of this result is that institutional reforms that increase efficiency in production will not necessarily promote environmental quality gains. Furthermore, the traditional time series argument that the EKC is a byproduct of economic growth based on the assumption that countries are identical bears an extra burden of proof. Therefore, empirical research on environmental quality and economic development needs further consideration.

This chapter also considered the effect of technologies that make capital less pollution intensive and environmental protection more effective. The results point to improved environmental quality and increased consumption and capital when these technologies are easily adopted. In the limiting case, highly clean capital enables a reduction in environmental protection expenditures.

Chapter 5

SUMMARY AND CONCLUSIONS

This dissertation investigates the optimal relationship between environmental quality and economic development. Chapter 2 develops a simple dynamic model of growth that is consistent with three empirical regularities: (i) decreasing and eventually increasing environmental quality as income grows (this is consistent with the EKC); (ii) negligible regulation and expenditures on environmental protection at early stages of a nation's development; and (iii) higher growth rates at earlier stages of development and slower growth at later stages, when better environmental quality is actively pursued. At early stages of development, when environmental quality is abundant relative to the stock of capital, the optimal decision for society is to accumulate capital without investing in environmental protection. As a result environmental quality declines at an increasing rate. Later on, as the optimal steady state ratio of capital to environmental quality is reached, expenditures on environmental protection contribute to social welfare and some resources are optimally diverted from consumption to preservation effort. In the steady state, consumption, environmental protection effort, environmental quality and the stock of capital all grow at the same rate.

Chapter 3 uses the framework of chapter 2 to study economies where at time zero, capital is abundant relative to environmental quality. This illustrates the plight of the transition economies of Central and Eastern Europe. These economies face much higher levels of environmental degradation than other economies with comparable income per capita. Furthermore, they are considerably heterogeneous amongst themselves with respect to both the degree of economic reform they have implemented and the actions taken to protect the environment. The model characterizes the transition economies and specifies the optimal path of environmental quality and environmental protection effort to be taken. Additionally, it derives a policy rule that takes the economy from the initial conditions to the optimal steady state ratio in finite time. This policy identifies the minimum level of environmental protection expenditures but does not guarantee the most rapid approach to the steady state. A variety of possibilities arise from the specified policy rule, which is consistent with the heterogeneous approach to environmental protection in the region. Finally, the optimal path towards the steady state contributes to the depressed economic activity observed in the region.

The framework of chapter 4 departs from the one in the previous chapters by abstracting from endogenous growth and focusing on technology adoption in different countries. The results show how country-specific characteristics can help explain the EKC in cross-section and panel data studies. In particular, differences in total factor productivity explain much of the income heterogeneity in the world and can cause the U-shaped pattern for environmental quality to emerge in cross-country data sets. Chapter 4 identifies the conditions under which differences in TFPs imply the EKC. Among them is the condition that the EKC will exist only if the aggregate environmental preservation function exhibits diminishing returns. The results of chapter 4 provide guidance to empirical research using cross-section and panel data to study the relationship between economic development and environmental quality. Also, besides the results for different TFPs, the model indicates that adoption of technologies that enhance the efficiency of environmental protection and reduce pollution intensity of capital will cause both environmental quality and consumption to increase.

In addition to better empirical tests of the EKC, three obvious extensions of this research emerge. The first one is consideration of a competitive equilibrium and mechanisms, such as taxes and permits, that are consistent with Pareto optimality as studied here. The second extension would analyze an open economy and possible strategic interaction between countries when transboundary pollution occurs. Would the EKC still be present in such scenario? The third extension, following Parente and Prescott (1994, 2000), is to explicitly model barriers to technology adoption in the pollution generation function and the environmental preservation function in a competitive equilibrium. This exercise could involve interactions between barriers to technology adoption in the production sector and barriers to adoption of technologies that enhance environmental protection efficiency and reduce pollution intensity of capital.

Appendix A

NECESSARY AND TRANSVERSALITY CONDITIONS

The Lagrangian for the maximization problem is: $\mathcal{L}_t = N[\alpha \ln(c_t) + (1-\alpha)\ln(E_t)] + \lambda_t[-PK_t + \Pi\pi_t + \xi E_t] + \mu_t[AK_t - Nc_t - \pi_t - \delta K_t] + \theta_t\pi_t$. Setting $\frac{\partial \mathcal{L}_t}{\partial c_t} = 0$ and $\frac{\partial \mathcal{L}_t}{\partial \pi_t} = 0$, yields equations (2.1) and (2.2). Equations (2.3) and (2.4) are obtained by setting $\dot{\lambda}_t = \rho\lambda_t - \frac{\partial \mathcal{L}_t}{\partial E_t}$ and $\dot{\mu}_t = \rho\mu_t - \frac{\partial \mathcal{L}_t}{\partial K_t}$.

Equation (2.4) is a differential equation for μ_t with solution:

$$\mu_t = e^{\left(\frac{P}{\Pi}+\rho+\delta-A\right)t}\left(\bar{\mu} - \frac{P}{\Pi}\int_0^t e^{-\left(\frac{P}{\Pi}+\rho+\delta-A\right)\tau}\theta_\tau d\tau\right)$$

where $\bar{\mu}$ is an arbitrary constant.

We can rewrite the transversality condition as in (2.5):

$$\lim_{t\to\infty} e^{-\rho t}e^{\left(\frac{P}{\Pi}+\rho+\delta-A\right)t}\left(\bar{\mu} - \frac{P}{\Pi}\int_0^t e^{-\left(\frac{P}{\Pi}+\rho+\delta-A\right)\tau}\theta_\tau d\tau\right)K_t = 0$$

Appendix B

STEADY STATE EQUATIONS

To obtain the differential equation (2.6) for consumption, differentiate equation (2.1) with respect to time and set it equal to equation (2.4), making use of equation (2.1) to substitute for μ_t and the fact that in the steady state an interior solution implies that $\theta_t = 0$:

$$-\frac{\alpha}{c_t}\frac{\dot{c}_t}{c_t} = \frac{\alpha}{c_t}\left(\frac{P}{\Pi} + \rho + \delta - A\right)$$

$$\frac{\dot{c}_t}{c_t} = \left(A - \frac{P}{\Pi} - \rho - \delta\right) \tag{B.1}$$

Equation (B.1) is an autonomous ODE with solution:

$$c_t = \tilde{c}e^{\varphi t} \tag{B.2}$$

where $\tilde{c}$ is a constant to be determined and $\varphi \equiv \left(A - \frac{P}{\Pi} - \rho - \delta\right)$.

Next, differentiate (2.2) with respect to time and set it equal to (2.3), making use of equation (2.1) to substitute for μ_t:

$$-\frac{1}{\Pi}\frac{\alpha}{c_t}\frac{\dot{c}_t}{c_t} = (\rho - \xi)\frac{1}{\Pi}\frac{\alpha}{c_t} - N\frac{(1-\alpha)}{E_t} \therefore$$

$$\frac{\dot{c}_t}{c_t} = N\Pi \frac{(1-\alpha)}{\alpha} \frac{c_t}{E_t} - \rho + \xi \tag{B.3}$$

Setting (B.1) equal to (B.3) yields:

$$\frac{c_t}{E_t} = \left(A - \frac{P}{\Pi} - \delta - \xi\right) \frac{1}{\Pi} \frac{\alpha}{(1-\alpha)} \frac{1}{N}$$

Or in a more simplified notation:

$$E_t = \phi c_t \tag{B.4}$$

Equation (B.4) must be satisfied for an optimal solution for the social planner's problem. Thus, from (B.2) and (B.4), we can derive the time path for environmental quality:

$$E_t = \phi c_t = \phi \tilde{c} e^{\varphi t} \tag{B.5}$$

But, since E_0 is given, equations (B.2) and (B.5) become:

$$E_t = E_0 e^{\varphi t} \tag{B.6}$$

$$c_t = \frac{E_0}{\phi} e^{\varphi t} \tag{B.7}$$

To derive the equations for K_t and π_t, first differentiate (B.6) with respect to time, set it equal to the equation of motion for environmental quality and solve for π_t:

$$E_0 \varphi e^{\varphi t} = -PK_t + \Pi \pi_t + \xi E_0 e^{\varphi t} \therefore$$

$$\pi_t = \frac{E_0 e^{\varphi t}(\varphi - \xi) + PK_t}{\Pi} \tag{B.8}$$

Next, substitute (B.7) and (B.8) into the equation of motion for the capital stock to obtain a differential equation for K_t and its respective solution:

$$\dot{K}_t = AK_t - N\frac{E_0}{\phi}e^{\varphi t} - \frac{E_0 e^{\varphi t}(\varphi - \xi)}{\Pi} - \frac{P}{\Pi}K_t - \delta K_t \therefore$$

$$\dot{K}_t - \left(A - \frac{P}{\Pi} - \delta\right) K_t = -\left(\frac{N}{\phi} + \frac{(\varphi - \xi)}{\Pi}\right) E_0 e^{\varphi t} \therefore$$

$$K_t = \left(\frac{N}{\phi} + \frac{(\varphi - \xi)}{\Pi}\right) \frac{E_0}{\rho} e^{\varphi t} + \tilde{K} e^{(\varphi + \rho)t} \tag{B.9}$$

To determine the constant $\tilde{K}$, plug equation (B.9) into the transversality condition (2.5), recalling that for an interior solution $\theta_t = 0$:

$$\lim_{t \to \infty} e^{-\rho t}\, \tilde{\mu}\, e^{-\varphi t} \left[\left(\frac{N}{\phi} + \frac{(\varphi - \xi)}{\Pi}\right) \frac{E_0}{\rho} e^{\varphi t} + \tilde{K} e^{(\varphi + \rho)t}\right] = 0 \therefore$$

$$\lim_{t \to \infty} \tilde{\mu} \left[\left(\frac{N}{\phi} + \frac{(\varphi - \xi)}{\Pi}\right) \frac{E_0}{\rho} e^{-\rho t} + \tilde{K}\right] = 0 \tag{B.10}$$

It follows from (B.10) that the transversality condition will hold if and only if $\tilde{K} = 0$. Therefore, as in (2.9), the equation for K_t becomes:

$$K_t = \left(\frac{N}{\phi} + \frac{(\varphi - \xi)}{\Pi}\right) \frac{E_0}{\rho} e^{\varphi t} \tag{B.11}$$

Plugging (B.11) into (B.8), we obtain the equation (2.10) for π_t:

$$\pi_t = \left[\frac{(\varphi - \xi)}{\Pi} + \frac{P}{\Pi}\left(\frac{N}{\phi} + \frac{(\varphi - \xi)}{\Pi}\right)\frac{1}{\rho}\right] E_0 e^{\varphi t} \tag{B.12}$$

Appendix C

TRANSITIONAL DYNAMICS EQUATIONS

To derive equations (2.13)–(2.15) for c_t, K_t and E_t during the transition to the steady state, first differentiate equation (2.1) with respect to time and substitute the result into equation (2.4):

$$\dot{\mu}_t = -\frac{\alpha \dot{c}_t}{c_t^2},$$

$$-\frac{\alpha \dot{c}_t}{c_t^2} = \frac{\alpha}{c_t}\left(\frac{P}{\Pi} + \rho + \delta - A\right) - \theta_t \frac{P}{\Pi}.$$

Rearranging, we obtain:

$$\dot{c}_t = \left(A - \frac{P}{\Pi} - \rho - \delta\right) c_t + \theta_t \frac{P}{\Pi \alpha} c_t^2. \tag{C.1}$$

Equation (C.1) is a Bernoulli differential equation with $n = 2$. To solve that equation, rewrite it as:

$$\frac{\dot{c}_t}{c_t} = \varphi + \theta_t \frac{P}{\Pi \alpha} c_t \tag{C.2}$$

Next, define $v_t = \frac{1}{c_t}$, so that $\dot{v}_t = -\frac{\dot{c}_t}{c_t^2}$, and divide both sides of (C.2) by c_t:

$$\frac{\dot{c}_t}{c_t^2} = \varphi\frac{1}{c_t} + \theta_t\frac{P}{\Pi\alpha} \tag{C.3}$$

Substitute v_t for $\frac{1}{c_t}$ in equation (C.3) and rearrange to obtain:

$$\dot{v}_t + \varphi v_t = -\theta_t\frac{P}{\Pi\alpha} \tag{C.4}$$

Equation (C.4) is an ODE with solution:

$$v_t = e^{-\varphi t}\left(\tilde{v} - \frac{P}{\Pi\alpha}\int_0^t \theta_\tau e^{\varphi\tau}d\tau\right) \tag{C.5}$$

Where $\tilde{v}$ is a constant. To obtain equation (2.13), substitute c_t for $\frac{1}{v_t}$ in equation (C.5), use the initial condition c_0, and rearrange. Finally, equations (2.14) and (2.15) are obtained by solving the differential equations $\dot{K}_t = AK_t - Nc_t - \delta K_t$ and $\dot{E}_t = -PK_t + \xi E_t$, and using the initial conditions K_0 and E_0.

Appendix D

TRANSITIONAL DYNAMICS EQUATIONS II

To derive the equations for c_t, E_t and π_t, first differentiate λ_t from equation (3.6) with respect to t and set the result equal to the right hand side of equation (3.7):

$$-\frac{\alpha}{\Pi}\frac{\dot{c}_t}{c_t^2} = \frac{\alpha}{\Pi}\frac{1}{c_t}(\rho - \xi) - \frac{N(1-\alpha)}{E_t}$$

Rearranging:

$$-\frac{\dot{c}_t}{c_t^2} = (\rho - \xi)\frac{1}{c_t} - \frac{(1-\alpha)}{\alpha}\frac{N\Pi}{E_t}$$

To solve the above Bernoulli differential equation, let $v_t = 1/c_t$, so that $\dot{v}_t = -\dot{c}_t/c_t^2$. This transformation produces an ordinary differential equation as follows:

$$\dot{v}_t = (\rho - \xi)v_t - \frac{(1-\alpha)}{\alpha}\frac{N\Pi}{E_t}$$

The solution to the above equation is:

$$v_t = \tilde{v}e^{(\rho-\xi)t} - N\Pi\frac{(1-\alpha)}{\alpha}\int_0^t \frac{e^{-(\rho-\xi)\tau}}{E_\tau}d\tau$$

Substituting c_t for $1/v_t$ and using c_0 for initial consumption yields:

$$c_t = \frac{c_0 e^{-(\rho-\xi)t}}{1 - \frac{N\Pi c_0(1-\alpha)}{\alpha}\int_0^t \frac{e^{-(\rho-\xi)\tau}}{E_\tau}d\tau}$$

To obtain the equation for π_t, plug the equations for K_t and c_t into $\pi_t = AK_t - Nc_t$:

$$\pi_t = AK_0 e^{-\delta t} - Nc_t$$

The get E_t, plug the equations for K_t and π_t into the equation of motion for environmental quality:

$$\dot{E}_t = -PK_0 e^{-\delta t} + \Pi[AK_0 e^{-\delta t} - Nc_t] + \xi E_t$$

The solution to the above ordinary differential equation and the initial condition E_0 produce:

$$E_t = -\frac{(\Pi A - P)}{(\delta+\xi)}K_0 e^{-\delta t} - e^{\xi t}\Pi N\int_0^t c_\tau e^{-\xi\tau}d\tau + \left[E_0 + \frac{(\Pi A - P)}{(\delta+\xi)}K_0\right]e^{\xi t}$$

Appendix E

PROOFS OF LEMMAS 1–3

Lemma 1 *The fixed point* $(0,0)$ *in the* ω-χ *phase plane is locally stable.*

Proof: For the point $(0,0)$ in the ω-χ phase plane, the terms a, b, c and d in equations (3.10) and (3.11) become:

$$a = -(\delta + \xi) - 2(\Pi A - P) \;\; ; \;\; b = 0 \;\; ; \;\; c = 0 \;\; ; \;\; d = -\rho$$

Therefore the eigenvalues of the system at $(0,0)$ are given by:

$$\nu = \frac{(a+d) \pm (a-d)}{2}$$

$$\nu_1 = a = -(\delta + \xi) - 2(\Pi A - P) < 0 \quad ; \quad \nu_2 = d = -\rho < 0$$

The two real negative eigenvalues imply that the fixed point $(0,0)$ is locally stable. ■

Lemma 2 *The fixed point* $\left(0, \frac{\alpha\rho}{\Pi N}\right)$ *in the* ω-χ *phase plane is locally unstable. Furthermore:*

(i) if $\alpha\rho \geq \delta + \xi$*, then the equilibrium is divergent;*

(ii) if $\alpha\rho < \delta + \xi$*, then the equilibrium exhibits a saddle path behavior.*

Proof: For the fixed point $\left(0, \frac{\alpha\rho}{\Pi N}\right)$ in the ω-χ phase plane, the terms a, b, c and d in equations (3.10) and (3.11) become:

$$a = \alpha\rho - \delta - \xi \ ; \ b = 0 \ ; \ c = -(\Pi A - P)\frac{\alpha\rho}{\Pi N} \ ; \ d = \rho$$

Therefore the eigenvalues of the system at $\left(0, \frac{\alpha\rho}{\Pi N}\right)$ are given by:

$$\nu = \frac{(a+d) \pm (a-d)}{2}$$

$$\nu_1 = a = \alpha\rho - (\delta + \xi) \gtrless 0 \quad ; \quad \nu_2 = d = \rho > 0$$

From the above, it follows that the system is locally unstable. Furthermore, if (i) $\alpha\rho \geq \delta + \xi$, then $\nu_1 \geq 0$ and the equilibrium is divergent; if (ii) $\alpha\rho < \delta + \xi$, then $\nu_1 < 0$ and the equilibrium exhibits a saddle path behavior. ■

Lemma 3 *Assume that* $\alpha\rho > \delta + \xi$, *then the fixed point* $\left(\frac{\alpha\rho-\delta-\xi}{(1-\alpha)(\Pi A-P)}, \frac{\alpha(\rho-\delta-\xi)}{(1-\alpha)\Pi N}\right)$ *in the* ω-χ *phase plane is locally unstable and exhibits a saddle path behavior.*

Proof: For the fixed point $\left(\frac{\alpha\rho-\delta-\xi}{(1-\alpha)(\Pi A-P)}, \frac{\alpha(\rho-\delta-\xi)}{(1-\alpha)\Pi N}\right)$ in the ω-χ phase plane, the terms a, b, c and d in equations (3.10) and (3.11) become:

$$a = -(\delta + \xi) - 2(\Pi A - P)\frac{(\alpha\rho - \delta - \xi)}{(1-\alpha)(\Pi A - P)} + \Pi N \frac{\alpha(\rho - \delta - \xi)}{(1-\alpha)\Pi N}$$

$$a = \frac{-\delta - \xi + \alpha\delta + \alpha\xi - 2\alpha\rho + 2\delta + 2\xi + \alpha\rho - \alpha\delta - \alpha\xi}{(1-\alpha)} = -\frac{(\alpha\rho - \delta - \xi)}{(1-\alpha)} < 0$$

$$b = \Pi N \frac{(\alpha\rho - \delta - \xi)}{(1-\alpha)(\Pi A - P)} > 0$$

$$c = -(\Pi A - P)\frac{\alpha(\rho - \delta - \xi)}{(1-\alpha)\Pi N} < 0$$

$$d = -\rho - (\Pi A - P)\frac{(\alpha\rho - \delta - \xi)}{(1-\alpha)(\Pi A - P)} + 2\frac{\Pi N}{\alpha}\frac{\alpha(\rho - \delta - \xi)}{(1-\alpha)\Pi N}$$

$$d = \frac{-\rho + \alpha\rho - \alpha\rho + \delta + \xi + 2\rho - 2\delta - 2\xi}{(1-\alpha)} = \frac{\rho - \delta - \xi}{(1-\alpha)} > 0$$

Consequently:

$$a + d = \rho \ ; \ a - d = \frac{-\rho(1+\alpha) + 2(\delta+\xi)}{(1-\alpha)} \ ; \ 4bc = -\frac{4\alpha(\rho - \delta - \xi)(\alpha\rho - \delta - \xi)}{(1-\alpha)^2}$$

Next, define $\Delta \equiv (a-d)^2 + 4bc$. Then:

$$\Delta = \frac{4(\delta+\xi)^2 - 4\rho(1+\alpha)(\delta+\xi) + \rho^2(1+\alpha)^2 - 4\alpha(\rho-\delta-\xi)(\alpha\rho-\delta-\xi)}{(1-\alpha)^2}$$

$$\Delta = \frac{4(\delta+\xi)^2(1-\alpha) - 4\rho(\delta+\xi)(1+\alpha)(1-\alpha) + \rho^2(1+\alpha)^2 - 4\alpha^2\rho^2}{(1-\alpha)^2}$$

and the eigenvalues of the system at $\left(\frac{\alpha\rho-\delta-\xi}{(1-\alpha)(\Pi A - P)}, \frac{\alpha(\rho-\delta-\xi)}{(1-\alpha)\Pi N}\right)$ are given by:

$$\nu = \frac{\rho \pm \sqrt{\Delta}}{2}$$

To see that the eigenvalues are real valued and of opposite signs, first notice that Δ is continuous and differentiable in $(\delta + \xi)$. Also, given $\alpha\rho > \delta + \xi$ and $\alpha; \rho; \delta; \xi > 0$, Δ is decreasing in $(\delta + \xi)$:

$$\frac{\partial\Delta}{\partial(\delta+\xi)} = \frac{8(\delta+\xi)(1-\alpha) - 4\rho(1+\alpha)(1-\alpha)}{(1-\alpha)^2} = \frac{4(1-\alpha)[-(\rho-\delta-\xi) - (\alpha\rho-\delta-\xi)]}{(1-\alpha)^2} < 0,$$

since $0 < \alpha < 1$. Thus, the infimum of the set of values for Δ is obtained when $\alpha\rho = (\delta+\xi)$, in which case $\Delta = \rho^2 > 0$, and the resulting eigenvalues are 0 and ρ as in Lemma 2 (i). Since Δ is decreasing in $(\delta + \xi)$, $0 < (\delta + \xi) < \alpha\rho$ implies that $\Delta > \rho^2 > 0$, and the smallest eigenvalue of the system will be negative. ■

Appendix F

PROOF OF PROPOSITION 3

In the steady state rates of growth of the economic variables of the model are equal to zero. To see that, start with the equations for (γ_c), (γ_π), (γ_K) and (γ_E):

$$\gamma_c \equiv \frac{\dot{c}_t}{c_t} = -\frac{1}{\sigma}\left(\frac{P_K}{\Pi_\pi} - F_K + \rho\right)$$

$$\gamma_\pi \equiv \frac{\dot{\pi}_t}{\pi_t} = \frac{1}{(\delta - 1)}\left(\gamma_c - \rho + N\frac{u_E}{u_c}\Pi_\pi\right)$$

$$\gamma_K \equiv \frac{\dot{K}_t}{K_t} = \frac{F(K_t) - Nc_t - \pi_t}{K_t}$$

$$\gamma_E \equiv \frac{\dot{E}_t}{E_t} = \frac{-P(K_t) + \Pi(\pi_t)}{E_t}$$

Proposition 3 *In the steady state the rates of growth of consumption (γ_c), environmental expenditures (γ_π), the stock of capital (γ_K) and environmental quality (γ_E) are equal to zero.*

Proof: The result can be proven by way of contradiction. Start with the capital stock, and suppose $\gamma_K > 0$. Then $K_t \to \infty$ and consequently $F_K \to 0$ and $P_K \to \infty$. Since γ_c is also constant, the equation for γ_c implies that $\pi_t \to 0$ so that $\Pi_\pi \to \infty$. Now, $K_t \to \infty$ and $\pi_t \to 0$ imply that $E_t \to 0$, not an optimal outcome, since $\lim_{E_t \to 0} u_E = \infty$.

Suppose now that $\gamma_K < 0$. Then $K_t \to 0$, $F_K \to \infty$ and $P_K \to 0$. A constant γ_c requires that $\pi_t \to \infty$, so that $\Pi_\pi \to 0$. But $K_t \to 0$ and $\pi_t \to \infty$ is a contradiction to the feasibility condition that $\pi_t = F(K_t) - Nc_t - \gamma_K K_t$.

Next, consider growth in consumption. Suppose $\gamma_c > 0$. Then $c_t \to \infty$ and that must result from ever increasing capital stock, i.e., $K_t \to \infty$. But as in the case for $\gamma_K > 0$, that yields a not optimal level of environmental quality. On the other hand, if $\gamma_c < 0$, then $c_t \to 0$ and that is also not optimal, since $\lim_{c_t \to 0} u_c = \infty$.

Lastly, since the stock of capital and consumption are constant in the steady state ($\gamma_K = \gamma_c = 0$), then aggregate income or production ($F(K_t)$) is also constant and consequently so is environmental preservation effort and environmental quality. ∎

Appendix G

COMPARATIVE STATICS

Total differention of (4.3)-(4.6) normalizing population so that $N = 1$ yields:

$$\begin{pmatrix} 0 & -\frac{\Pi_{\pi\pi}}{\Pi_\pi^2}P_K & 0 & \frac{P_{KK}}{\Pi_\pi} - F_{KK} \\ \Pi_\pi u_{Ec} - \rho u_{cc} & \Pi_{\pi\pi}u_E & \Pi_\pi u_{EE} - \rho u_{cE} & 0 \\ 0 & \Pi_\pi & 0 & -P_K \\ -1 & -1 & 0 & F_K \end{pmatrix} \cdot \begin{pmatrix} dc \\ d\pi \\ dE \\ dK \end{pmatrix} =$$

$$\begin{pmatrix} F_K^\circ dA - \frac{P_K^\circ}{\Pi_\pi}dB + \frac{\Pi_\pi^\circ}{\Pi_\pi^2}P_K dD \\ 0dA + 0dB - \Pi_\pi^\circ u_E dD \\ 0dA + P^\circ dB - \Pi^\circ dD \\ -F^\circ dA + 0dB + 0dD \end{pmatrix}$$

To simplify notation, rewrite the above as:

$$\begin{pmatrix} 0 & x_1 & 0 & x_2 \\ x_3 & x_4 & x_5 & 0 \\ 0 & \Pi_\pi & 0 & -P_K \\ -1 & -1 & 0 & F_K \end{pmatrix} \cdot \begin{pmatrix} dc \\ d\pi \\ dE \\ dK \end{pmatrix} = \begin{pmatrix} F_K^\circ dA - z_1 dB + z_2 dD \\ 0dA + 0dB - z_3 dD \\ 0dA + P^\circ dB - \Pi^\circ dD \\ -F^\circ dA + 0dB + 0dD \end{pmatrix}$$

Let Λ represent the the first matrix on the left hand side. Then its determinant is given by the expression below:

$$\det(\Lambda) = -x_5(x_1 P_K + x_2 \Pi_\pi) > 0$$

Apply Cramer's rule to calculate the derivative of environmental quality with respect to changes in A (changes in total factor productivity):

$$\frac{dE}{dA} = \frac{1}{\det(\Lambda)} \cdot \det \begin{pmatrix} 0 & x_1 & F_K^\circ & x_2 \\ x_3 & x_4 & 0 & 0 \\ 0 & \Pi_\pi & 0 & -P_K \\ -1 & -1 & -F^\circ & F_K \end{pmatrix}$$

$$= \frac{1}{\det(\Lambda)} \left[-x_3 \det \begin{pmatrix} x_1 & F_K^\circ & x_2 \\ \Pi_\pi & 0 & -P_K \\ -1 & -F^\circ & F_K \end{pmatrix} + \det \begin{pmatrix} x_1 & F_K^\circ & x_2 \\ x_4 & 0 & 0 \\ \Pi_\pi & 0 & -P_K \end{pmatrix} \right]$$

$$= \frac{1}{\det(\Lambda)} [-x_3(F_K^\circ P_K - x_2 F^\circ \Pi_\pi - x_1 F^\circ P_K - \Pi_\pi F_K F_K^\circ) + x_4 F_K^\circ P_K]$$

$$= \frac{1}{\det(\Lambda)} \left[-x_3 \left[F_K^\circ \Pi_\pi \left(\frac{P_K}{\Pi_\pi} - F_K \right) - F^\circ(x_2 \Pi_\pi + x_1 P_K) \right] + x_4 F_K^\circ P_K \right]$$

$$= \frac{1}{\det(\Lambda)} [-x_3[-\rho F_K^\circ \Pi_\pi - F^\circ(x_2 \Pi_\pi + x_1 P_K)] + x_4 F_K^\circ P_K] \gtrless 0$$

Where the last equality follows from equation (4.3). Derivation of the the remaining derivatives follows from the application of Cramer's rule. The results follow:

$$\frac{dE}{dB} = \frac{1}{\det(\Lambda)} [-x_3[\rho z_1 \Pi_\pi + P^\circ(x_1 F_K + x_2)] + x_4(x_2 P^\circ - z_1 P_K)] \gtrless 0$$

$$\frac{dE}{dD} = \frac{1}{\det(\Lambda)} [-x_3[-\rho z_2 \Pi_\pi - \Pi^\circ(x_1 F_K + x_2)] + x_2(z_3 \Pi_\pi - x_4 \Pi^\circ)] > 0$$

$$\frac{dc}{dA} = \frac{1}{\det(\Lambda)}[-x_5[\rho F_K^{\circ}\Pi_\pi + x_1 P_K F^{\circ} + x_2 F^{\circ}\Pi_\pi]] > 0$$

$$\frac{dc}{dB} = \frac{1}{\det(\Lambda)}[x_5(\rho z_1 \Pi_\pi + x_2 P^{\circ} + x_1 F_K P^{\circ})] < 0$$

$$\frac{dc}{dD} = \frac{1}{\det(\Lambda)}[-x_5(\rho z_2 \Pi_\pi + x_2 \Pi^{\circ} + x_1 F_K \Pi^{\circ})] > 0$$

$$\frac{d\pi}{dA} = \frac{1}{\det(\Lambda)}[-x_5 F^{\circ} P_K] > 0$$

$$\frac{d\pi}{dB} = \frac{1}{\det(\Lambda)}[x_5(z_1 P_K - x_2 P^{\circ})] \gtrless 0$$

$$\frac{d\pi}{dD} = \frac{1}{\det(\Lambda)}[-x_5(z_2 P_K - x_2 \Pi^{\circ})] \gtrless 0$$

$$\frac{dK}{dA} = \frac{1}{\det(\Lambda)}[-x_5 \Pi_\pi F_K^{\circ}] > 0$$

$$\frac{dK}{dB} = \frac{1}{\det(\Lambda)}[x_5(x_1 P^{\circ} + z_1 \Pi_\pi)] < 0$$

$$\frac{dK}{dD} = \frac{1}{\det(\Lambda)}[-x_5(x_1 \Pi^{\circ} + z_2 \Pi_\pi)] > 0$$

Appendix H

PROOFS OF PROPOSITION 4 AND COROLLARY 1

Proposition 4 *The derivative of environmental quality with respect to the total factor productivity (TFP) depends on the curvature of the utility and environmental protection functions as follows:* $\frac{dE}{dA} \gtrless 0$ *if and only if* $\frac{\Pi_{\pi\pi}}{\Pi_\pi}\frac{d\pi}{dA} \gtrless \left(\frac{u_{cc}}{u_c} - \frac{u_{Ec}}{u_E}\right)\frac{dc}{dA}$.

Proof: To determine the condition for the sign of the effect of different TFPs on environmental quality, focus on the expression for dE/dA from appendix G substituting x_1, x_2, x_3 and x_4 with their corresponding expressions and using the normalization $N = 1$:

$$\frac{dE}{dA} \gtrless 0 \Leftrightarrow$$

$$\Pi_{\pi\pi} u_E F_K^\circ P_K \gtrless -(\Pi_\pi u_{Ec} - \rho u_{cc})\left\{\rho F_K^\circ \Pi_\pi + F^\circ\left[\left(\frac{P_{KK}}{\Pi_\pi} - F_{KK}\right)\Pi_\pi - \frac{\Pi_{\pi\pi}}{\Pi_\pi^2}P_K^2\right]\right\}$$

$$\Pi_{\pi\pi} u_E \gtrless \Pi_\pi\left(\frac{\rho}{\Pi_\pi}u_{cc} - u_{Ec}\right)\left\{\rho\frac{\Pi_\pi}{P_K} + \frac{F^\circ}{F_K^\circ P_K}\left[\left(\frac{P_{KK}}{\Pi_\pi} - F_{KK}\right)\Pi_\pi - \frac{\Pi_{\pi\pi}}{\Pi_\pi^2}P_K^2\right]\right\}$$

The term within braces on the right hand side of the expression above corresponds to the ratio of dc/dA to $d\pi/dA$. Also make use of equation (4.4) to substitute u_E/u_c for ρ/Π_π and rewrite the above condition as follows:

$$\frac{\Pi_{\pi\pi}}{\Pi_{\pi}} \gtrless \frac{1}{u_E}\left(\frac{u_E}{u_c}u_{cc} - u_{Ec}\right)\frac{dc/dA}{d\pi/dA}$$

$$\frac{\Pi_{\pi\pi}}{\Pi_{\pi}}\frac{d\pi}{dA} \gtrless \left(\frac{u_{cc}}{u_c} - \frac{u_{Ec}}{u_E}\right)\frac{dc}{dA}$$

■

Alternative proof: First notice that the system of equations describing the steady state is block recursive. Use equations (4.3), (4.5) and (4.6) to solve for c, π and K as functions of the model parameters. Next, apply the implicit function theorem to equation (4.4) to obtain:

$$\frac{dE}{dA} = \frac{\Pi_{\pi\pi}\frac{d\pi}{dA}u_E + u_{Ec}\Pi_{\pi}\frac{dc}{dA} - \rho u_{cc}\frac{dc}{dA}}{-\Pi_{\pi}u_{EE} + \rho u_{cE}} \gtrless 0$$

$$\Leftrightarrow \quad \frac{d\pi}{dA}\frac{\Pi_{\pi\pi}}{\Pi_{\pi}}\Pi_{\pi}u_E \gtrless (\rho u_{cc} - u_{Ec}\Pi_{\pi})\frac{dc}{dA}$$

$$\Leftrightarrow \quad \frac{\Pi_{\pi\pi}}{\Pi_{\pi}}\frac{d\pi}{dA}u_c\rho \gtrless (\rho u_{cc} - u_{Ec}\frac{u_c\rho}{u_E})\frac{dc}{dA},$$

where the last expression was obtained by making use of equation (4.4). Rearranging:

$$\frac{dE}{dA} \gtrless 0 \quad \Leftrightarrow \quad \frac{\Pi_{\pi\pi}}{\Pi_{\pi}}\frac{d\pi}{dA} \gtrless (\frac{u_{cc}}{u_c} - \frac{u_{Ec}}{u_E})\frac{dc}{dA}$$

■

Corollary 1 *Define the utility function as* $u(c_t, E_t) = \varphi\frac{c_t^{1-\sigma}-1}{1-\sigma} + \psi\frac{E_t^{1-\beta}-1}{1-\beta}$, *where* $\sigma, \beta, \varphi, \psi >$

0, *and the environmental protection function as* $D\Pi^{\circ}(\pi_t) = D\pi_t^{\delta}$, *where* $0 < \delta < 1$. *Then,*

$$\frac{dE}{dA} \gtrless 0 \quad \textit{if and only if} \quad \sigma\eta_c^A \gtrless (1-\delta)\eta_\pi^A,$$

where $\eta_c^A = \frac{dc}{dA}\frac{A}{c}$ *and* $\eta_\pi^A = \frac{d\pi}{dA}\frac{A}{\pi}$ *are the elasticities of consumption and environmental expenditures with respect to the total factor productivity.*

Proof: For the utility and environmental protection functions defined above,

$$\frac{\Pi_{\pi\pi}}{\Pi_\pi} = \frac{(\delta-1)}{\pi}, \quad \frac{u_{cc}}{u_c} = -\frac{\sigma}{c} \quad \text{and} \quad u_{Ec} = 0.$$

Plugging these expressions into the result of proposition 4 yields:

$$\frac{(\delta-1)}{\pi}\frac{d\pi}{dA} \gtrless -\frac{\sigma}{c}\frac{dc}{dA}.$$

Multiplying both sides by A we obtain:

$$(\delta-1)\frac{A}{\pi}\frac{d\pi}{dA} \gtrless -\sigma\frac{A}{c}\frac{dc}{dA}$$

Rearranging:

$$\sigma\eta_c^A \gtrless (1-\delta)\eta_\pi^A,$$

where $\eta_c^A = \frac{dc}{dA}\frac{A}{c}$ and $\eta_\pi^A = \frac{d\pi}{dA}\frac{A}{\pi}$ are the elasticities of consumption and environmental expenditures with respect to the to the total factor productivity. ■

Appendix I

DYNAMIC SYSTEM STABILITY

The conditions for optimality in our model are given by the system of differential equations (4.1), (4.2) and the equations of motion for E_t and K_t:

$$\dot{c}_t = \frac{u_c}{u_{cc}}(\frac{P_K}{\Pi_\pi} - F_K + \rho) - \frac{u_{cE}}{u_{cc}}\dot{E}_t$$

$$\dot{\pi}_t = \frac{\Pi_\pi}{u_c \Pi_{\pi\pi}}[u_{cc}\dot{c}_t + u_{cE}\dot{E}_t + \Pi_\pi u_E - \rho u_c]$$

$$\dot{E}_t = -P(K_t) + \Pi(\pi_t)$$

$$\dot{K}_t = F(K_t) - Nc_t - \pi_t$$

Linearization of the above system around the steady state yields:

$$\begin{pmatrix} \dot{c}_t \\ \dot{\pi}_t \\ \dot{E}_t \\ \dot{K}_t \end{pmatrix} =$$

$$
= \begin{pmatrix} 0 & -\frac{u_c \frac{\Pi_{\pi\pi}}{\Pi_\pi^2} P_K + u_{cE} \Pi_\pi}{u_{cc}} & 0 & \frac{u_c(\frac{P_{KK}}{\Pi_\pi} - F_{KK}) + u_{cE} P_K}{u_{cc}} \\ \frac{-\rho \Pi_\pi u_{cc} + \Pi_\pi^2 u_{Ec}}{\Pi_{\pi\pi} u_c} & -\frac{P_K}{\Pi_\pi} + \frac{\Pi_\pi u_E}{u_c} & \frac{-\rho \Pi_\pi u_{cE} + \Pi_\pi^2 u_{EE}}{\Pi_{\pi\pi} u_c} & \frac{\Pi_\pi(\frac{P_{KK}}{\Pi_\pi} - F_{KK})}{\Pi_{\pi\pi}} \\ 0 & \Pi_\pi & 0 & -P_K \\ -1 & -1 & 0 & F_K \end{pmatrix}
$$

$$
\cdot \begin{pmatrix} c_t - c^* \\ \pi_t - \pi^* \\ E_t - E^* \\ K_t - K^* \end{pmatrix} + R^{(2)}
$$

Where, the first matrix on the right hand side is evaluated at the steady state values of the variables and $R^{(2)}$ is the remainder of the Taylor expansion involving derivatives of second order and higher. The remainder is assumed to be negligible in a sufficiently small neighborhood of the steady state. The steady state values of the variables are denoted here by "*". If we define $\tilde{x}_t = (x_t - x^*)$, we can rewrite the above system as $\dot{\tilde{x}}_t = \Gamma \cdot \tilde{x}_t$, and stability of the above system will be given by the eigenvalues of Γ. For the steady state $c^* = 9.289$, $\pi^* = 0.335$, $K^* = 0.896$, and $E^* = 441.96$, given by the initial parameters, two positive and two negative eigenvalues result (7.797, −7.780, 0.035 and −0.012). This means that the system of differential equations describing optimality in the problem exhibits saddle path stability around the steady state.

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