The Relevance and Implications of the Environmental Kuznets Curve under Stock Effects and Non-Linearities: A Hysteresis Based Approach

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Introduction

The environmental Kuznets curve describes an inverted U-shaped relationship between environmental pollution and income, which, if it is a valid description of the true relationship between environmental pollution and economic development, suggests that beyond a threshold level of development, continued economic growth is good for the environment. The policy implication drawn by some, and disputed by others, is that environmental protection will come about more or less autonomously as a result of strong pro-growth policies (see Arrow et al. 1995 for a nice discussion of such issues).

Such analyses often focus on pollution as a flow phenomenon; greater levels of development may lead to stricter environmental regulations and a reduction in the generation of new pollution. However, the environmental damage generated by many pollutants may be more a function of the existing stock of pollutant than of its flow; stock effects may trigger loss of system resilience or irreversibilities in the evolution of environmental quality that influence the options available to future generations (Arrow et al. 1995).

Irreversibility is the more extreme of the “threshold effects” in environmental quality change. An example of irreversible change from the atmospheric stock of carbon dioxide and other greenhouse gasses, for instance, would be a rise sea level or a breakdown of the thermohaline circulation belt (Gjerde et al. 1999, Keller et al. 2000). Hysteresis, on the other hand, refers to an intermediate stock effect, where declines in environmental quality are potentially reversible, but at a much higher cost than would have been associated with prevention of the quality decline in the first place. This phenomenon occurs when the level of pollution stock associated with the system flipping into a degraded state is much higher than that required for the system to return to a pristine state[1]. Therefore, the stock of pollutants needs to be lowered to a level beyond its flipping threshold in order to enable it to return to a pristine state. Though the problem of hysteresis has been widely analyzed in ecological sciences (Ludwig et al. 1978), the economics of it has been taken up only recently (Maler et al. 2000).

Elaborating on the concept of stock effects in the presence of an EKC, Munasinghe (1999) emphasizes the need to explore alternative paths that allow one to attain high levels of consumption and income without generating large stocks of pollution and severely degrading the environment. He proposes that in the presence of stock effects, a more desirable transition toward higher income levels may pass through a 'tunnel' in the inverted U-shaped curve (presented as a metaphorical hill) such that the irreversibilities associated with the thresholds levels of stock pollution could be avoided.

In this paper we construct a model around the ideas discussed in Arrow et al (1995) and Munasinghe (1999) to explore the implications for optimal rates and levels of capital accumulation when pollution related stock externalities are taken into consideration. We expand the existing theoretical models in the literature on EKC to incorporate the irreversibilities and hysteresis effects that may exist between flow of pollution and environmental quality. In our model the incorporation of hysteresis between environmental quality and the flow of pollution implies that it may not be optimal to increase the pollution all the way up to the threshold level implied by a conventional EKC relationship. This is primarily due to the fact that once the stock pollution level

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[1] Throughout the paper, we use the term degraded and pristine to characterize the states of an ecological system that are clearly distinguishable in terms of their pollutant contents and ecological services rendered. Similar terminology could be found in the existing literature. For example, Maler et al. (2000) while looking at the nutrient loadings in a lake characterize the states as clear (or oligotrophic) and turbid (eutrophic).

crosses a threshold beyond which hysteresis sets in, the cost of reversing the impacts of the pollution stock may become excessively high. Consequently, even though a conventional EKC may exist between pollution flow and income, there may not exist a similar relationship between certain indicators of environmental quality and income.

In addition to an analysis of the optimal transition path, we look at the case of a competitive economy that does not incorporate the externalities associated with pollution emissions. The implications for steady state levels of pollution and capital are characterized and compared to the socially optimal case when stock effects are taken into consideration. We show that multiple steady states exist, and that achievable steady states are history-dependent; since different countries exhibit different initial combinations environmental quality and capital, they may end up on different stable paths. One important finding from the above analysis is that the optimal levels and rates of capital accumulations are significantly different for the competitive and the socially optimal cases. This raises the question of whether tunneling may be feasible in the absence of significant pollution reducing technological advances.

In the following sections a theoretical model is designed that incorporates the hysteresis effects associated with stock accumulations. Introduction of hysteresis makes the model non-linear and renders most analytical exposition intractable. We therefore perform numerical simulations in order to explore the issues raised above.

Model

Two arguments have been offered to explain the existence of an EKC. One hinges on the assumption that people have a preference for environmental quality that increases disporportionatley as income rises. This is a simple case of non-homothetic preferences. The second explanation is based upon an assumption of pollution-reducing technological progress that causes pollution levels to fall as income rises[2]. Since our focus is on optimal transition paths in the presence of an EKC and not on theoretically exploring the merits of each theory, we incorporate both these aspects into the model. The relative importance of either aspect is then merely a matter of parameter specification. The outline of the model is described below.

The production function exhibits decreasing returns to scale in capital (*k*) given by[3]:

(1) $m = k^{\alpha}$ where $\alpha < 1$.

Pollution rises with output, but at a decreasing rate. This allows for pollution-reducing technological progress with capital. γ is the parameter that associates technological progress with capital accumulation[4].

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[2] This argument makes the assumption that a threshold level of income exists beyond which less polluting technologies could be used efficiently. However, in absence of conclusive empirical estimates, these theories have been subjected to severe criticisms and counter-theories. Further, the concern against any pollution-reducing technological progress has been that though such technologies may reduce the emissions of one type of pollutants they lead to other kinds of toxic accumulations in the long run.

[3] The role of population as another factor of production is ignored here to keep the analysis tractable. However, population may have implications on the existence of the EKC itself and also on the environmental degradation associated with growth. For example, with increasing population, per capita income may still remain low enough than may be required in order to trigger a shift in the environmental preferences. Also, increasing demographic pressures may make the environment more susceptible to the irreversibilities.

(2) $$p = \beta k^{\alpha-\gamma}$$

Capital accumulation is determined by:

(3) $$\dot{k} = k^{\alpha} - c - \delta k$$

where c is consumption and δ is the rate of depreciation of capital. Environmental quality (d) degrades as:

(4) $$\dot{d} = \theta p + \eta \frac{d^n}{d^n + d_0} - \rho d$$

In the above equation the change in environmental quality is sensitive to both pollution flow and stock**.** Ecological systems are often characterized by hysteresis in which the system flips from a ‘pristine’ state to a ‘degraded’ state with the crossing of a threshold level of the stock of pollutant. This flipping is unique in the sense that costs of bringing the system back into ‘pristine’ state may be far greater than the costs associated with preventing the ‘pristine’ state from falling into the ‘degraded’ state. The second term on the right hand side introduces the hysteresis effect. η is the maximum rate at which environmental quality degrades. The third term represents the regenerative capacity of the environment, in which ρ is the rate of environmental regeneration.

The utility function is additively separable in consumption and environmental quality and is given as:

(5) $$u = aLog(c) - bLog(d)$$

In the above equation the parameter ‘*b*’ affects the role environmental preferences play in the determination of the EKC. Society maximizes its utility from consumption net of

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[4] See Beltratti (1996) for similar formulations.

disutility from environmental quality degradation over an infinite horizon, subject to a discount rate *r*. The current value Hamiltonian is written as:

$$(6)\qquad cvh = aLog(c) - bLog(d) + \lambda_1(k^{\alpha} - c - \delta k) + \lambda_2(\theta p + \eta\frac{d^n}{d^n + d_0} - \rho d)$$

The first order condition taken with respect to consumption is given by:

$$(7)\qquad \lambda_1 = \frac{a}{c}$$

Equation (7) above requires that the marginal utility from consumption be equated to its shadow price along its optimal path. The arbitrage conditions for evolution of capital and stock of degradation are given by (8) and (9):

$$(8)\qquad \dot{\lambda}_1 = \lambda_1(\delta + r - \alpha k^{\alpha-1}) - \lambda_2\theta\beta(\alpha-\gamma)k^{\alpha-\gamma-1}$$

Note that the shadow price of capital is negatively related to the shadow price of degradation as each additional unit of capital leads to more pollution which adds to the stock of degradation. The shadow price of stock of degradation, on the other hand, falls with the rise in stock as degradation is a ‘bad’.

$$(9)\qquad \dot{\lambda}_2 = \left\{\frac{b}{d} - \lambda_2(\eta\frac{nd^{n-1}d_0}{(d^n + d_0)^2} - \rho - r)\right\}$$

Consequently, the implications for rate of growth of consumption can be derived from (7) and (8):

$$(10)\qquad \frac{\dot{c}}{c} = \alpha k^{\alpha-1} - \delta - r + \lambda_2\frac{\theta\beta c}{a}(\alpha-\gamma)k^{\alpha-\gamma-1}$$

The time paths are explored later on with the help of numerical simulations. However, first we explore the effect of hysteresis on the system dynamics and the location and characterization of system steady states.

Steady State Analysis

In steady state the rates of growths of all the state variables and their shadow prices are assumed to be zero. This is solved in the following equations:

$$\dot{c} = 0 \Rightarrow \lambda_2 = \frac{-\alpha k^{\alpha-1} + \delta + r}{\frac{\theta\beta c}{a}(\alpha - \gamma)k^{\alpha-\gamma-1}} \tag{11}$$

$$\dot{\lambda}_2 = 0 \Rightarrow \lambda_2 = \frac{b}{d\left\{\frac{\eta n d_0 d^{n-1}}{(d^n + d_0)^2} - \rho - r\right\}} \tag{12}$$

$$\dot{k} = 0 \Rightarrow c = \kappa^{\alpha} - \delta k \tag{13}$$

$$\dot{d} = 0 \Rightarrow p = \frac{1}{\theta}\left\{\rho d - \eta\frac{d^n}{d^n + d_0}\right\} \tag{14}$$

This gives a system with four equations and four unknowns that can be used to determine the steady state values of capital and degradation. Substituting (13) into (11) we get:

$$\lambda_2 = \frac{-\alpha k^{\alpha-1} + \delta + r}{\frac{\theta\beta(\kappa^{\alpha} - \delta k)}{a}(\alpha - \gamma)k^{\alpha-\gamma-1}} \tag{15}$$

Equating (15) and (12) we get:

$$\frac{b}{d\left\{\frac{\eta n d_0 d^{n-1}}{(d^n + d_0)^2} - \rho - r\right\}} = \frac{-\alpha k^{\alpha-1} + \delta + r}{\frac{\theta\beta(\kappa^{\alpha} - \delta k)}{a}(\alpha - \gamma)k^{\alpha-\gamma-1}} \tag{16}$$

Equation (16) gives a relationship between capital and the level of environmental degradation and so does (14). Equations (14) and (16) when solved simultaneously would give the steady state levels of capital and degradation. However, due to the non-linearities associated with the evolution of environmental degradation, it is not possible to explicitly solve for the steady state values of capital, pollution, consumption, and environmental degradation. We therefore make use of numerical simulations to characterize these values. Table 1 below presents the value of parameters assumed for the purpose of numerical simulations. It is hard to get realistic estimates of such parameters, especially at a global level; therefore their significance should be understood only relative to each other.

INSERT TABLE 1 HERE

The results of the simulations are illustrated through figures. These simulations involve steady state analyses using MATHEMATICA and dynamic analyses using GAMS. Figure 1 presents the relationship between capital and environmental degradation. Notice that environmental degradation is irreversible once it exceeds 1.5 and capital exceeds 100. Beyond that level the system flips into a 'degraded' state from which it is impossible to flip back into the 'pristine' environment. This can be seen from the fact that in the 'degraded' environment the degradation level associated with a stock of 100 units of capital is 4 and to bring it back to a level below 2, capital needs to be almost totally 'de-accumulated'[5]. This reflects the fact that high levels of degradation may trigger irreversible changes in the quality of the environment, which may at best be extremely costly to revert back to.

INSERT FIGURE 1 HERE

Next we look at the behavior of the shadow price of degradation in steady state. Figure 2 represents the shadow price of the stock of degradation along the isoclines representing the relationship between capital and degradation. Notice that the shadow price of degradation is negative (in most parts) as degradation is a 'bad' commodity. This is

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[5] However, with a lesser hysteresis effect flipping back may be possible though capital would still need to be lowered significantly in order to flip.

represented by the two curves in the regions I and II, which fall to the left and right sides of the two asymptotes respectively. However, the region in between the two asymptotes (region III) shows a positive value for the shadow price of degradation that reaches infinity asymptotically. This happens due the fact that such regions are the flipping points for the system. For example, notice that as the level of degradation reaches the left asymptote from the left hand side (region I), the shadow price of degradation reaches negative infinity, reflecting the fact that the system would flip into the degraded state beyond that point which would be extremely harmful. Thus the system would be 'screeching' to a halt at this point. On the other hand to the right hand side of the left asymptote (region III), the shadow price of the stock of degradation goes to positive infinity reflecting its 'desperation' to reduce the level of stock marginally in order to flip into the 'pristine' environment. Similar logic would explain the behavior of shadow price on the right asymptote.

INSERT FIGURE 2 HERE

The hysteresis (irreversibility) evident in the relationship between capital accumulation and degradation arises primarily from the relation specified between the 'flow' of pollution and the 'stock' of degradation. Figure 3 depicts this relationship along the $\dot{d} = 0$ isoclines. Once the system flips into the 'degraded' state, the flow of pollution needs to be reduced to a lower level than before in order for the system to flip back into the 'pristine' state.

INSERT FIGURE 3 HERE

Figure 4 shows a similar hysteresis (irreversible) effect associated with consumption and degradation. Notice that in our model we do not allow for elimination of pollution through abatement, therefore consumption is the only control variable available at hand. The multiple intersections on the X-axis can be attributed to the non-linearities of the system.

INSERT FIGURE 4 HERE

Figure 5 gives the socially optimum steady state level of capital and degradation. At least four steady states (denoted S1, U2, U3 and S4) are possible. From the dynamics of the capital and degradation stocks it can be easily deduced that the two extreme points (S1 and S4) are the stable ones with the middle two (U2 and U3) being unstable. The steady state, S4, to right given by high levels of capital and environmental degradation represents the ‘degraded’ steady state whereas the steady state, S1, on the left represents the one with a ‘pristine’ level of environment. A country’s portfolio of environmental quality and capital stock when it enters the system would determine whether its optimal path is on a stable arm proceeding toward the left steady state or toward the right steady state.

INSERT FIGURE 5 HERE

The dynamics of the system’s optimal development path are shown in figure 6 for a very low initial capital level of 0.5 and an initial level of environmental degradation of 2.5. On the scale of values chosen, 2.5 should be associated with high levels of degradation, however, notice that the system still manages to return to the ‘pristine’ steady state. Also notice the drop in the level of environmental degradation as pollution falls and capital stabilizes. This represents the happy story of the environmental Kuznets curve—the promise of achieving higher levels of capital and higher levels of environmental quality made possible by high economic growth. However we will show that there are problems with pre-supposing such a path, especially when one considers an economy characterized by myopic behavior of competitive agents.

INSERT FIGURE 6 HERE

Next we look at an economy with low levels of capital and environmental degradation. Such economies are characterized by a heavy emphasis on capital accumulation with little or no disutility from environmental degradation. Therefore we model such an economy by neglecting the disutility from environmental degradation in their welfare functions. The rest of the dynamics remain the same as the socially optimum case. The steady state level of capital (drawn as a straight line) is compared to the socially optimal case in figure 7 below. Notice the steady state level of capital is now unaffected by the level of environmental degradation. For this reason the intersection points in the figure no longer represent the steady states for environmental degradation.

INSERT FIGURE 7 HERE

How does this compare with the socially optimum case? The pristine levels of capital are much lower in the socially optimal case as compared to the competitive case; however, the steady states associated with the degraded environment show similar levels of capital accumulation.

Implications for Currently Industrializing Economies

So what are the lessons for the currently industrializing economies? If high levels of capital accumulations are linked with hysteresis in the evolution of environmental quality, what should be the optimal levels and rate of such accumulations? And finally do initial endowments matter? In this section we look at these issues. Figure 8 below shows the dynamics of pollution, capital accumulation and degradation along the competitive economy path for an economy endowed with low levels of capital but high levels of environmental degradation. In this case the economy settles into the 'degraded' state in the long run. As indicated by the simulation, the combination of initial levels of capital and environmental degradation is crucial in determining whether an economy along the competitive path would be able to retain its pristine environmental sate and still maintain high levels of capital accumulation or would flip into a degraded state as it industrializes.

INSERT FIGURE 8 HERE

We explore this issue by looking at the threshold level of initial environmental degradation for a given level of initial capital beyond which the economy settles into the degraded state. For the values of the parameters presented in Table 1, we find that for an initial level of environmental capital of 0.5, this threshold is achieved at the level of degradation of 2.371. If an economy starts with a higher level of degradation, it would shift into a 'degraded' state, whereas, if it started with a level lower than the above threshold it would settle into the 'pristine' state. This is shown in the figures 9 and 10 below.

INSERT FIGURE 9 & 10 HERE

Are the economies that are characterized by levels of degradation above the threshold doomed? A simple solution in that case would be to lower the initial endowments and thus affect the rate at which capital grows. This fact is reflected in figures 9 and 10 where with an initial level of capital of 0.25, the 'pristine' levels of environment could be achieved while still maintaining high levels of consumption. This does show a ‘tunnel’ out of the hysteresis and irreversibilities associated with the ‘turning point’ levels of degradation as proposed by Munasinghe (1999). However, there is a price to be paid in the form of low levels of steady state capital.

Point of No Return

A crucial question asks how currently industrializing countries can grow and still avoid the kind of irreversibilities (or at best high costs) associated with the transition of their natural environments into ‘degraded’ states. As mentioned above, an economy with a heavy emphasis on growth and little or no regard for environmental degradation would fall into a degraded state if its initial endowments are on the wrong side of the threshold. The literature on EKC has assumed that preferences for environmental quality exist right from the start of the industrialization process and therefore, an economy crossing a threshold ratio of environmental quality to degradation will experience a drop in levels of pollution. However, this stylized representation of preferences masks the complexity of the role that information plays. The process of industrialization has often been characterized by a rapid increase in capital simultaneously with a rapid degradation of environment. The information about the health costs associated with environmental pollution and the economic and ecological damages from a stock build-up became available only in the advanced stages of a country’s growth. Preference for environmental quality may in fact take discrete jumps as more information becomes available and the uncertainty associated with the impacts of environmental degradation is removed. The recent controversy over the impacts of global warming is a glaring example.

The above idea could be incorporated into our model by assuming that countries start with a heavy emphasis on growth (characterized by the competitive path), but that as information about environmental degradation becomes available, there is a 'regime' change after which the socially optimal growth path is adopted. This regime change may be either endogenously specified (for example, the environmental utility parameter '*b*' becoming non-zero beyond a certain ratio of capital and degradation) or exogenously specified based upon the observation of currently industrialized economies. The critical element in determining the long-term effect of a regime change is at what point it occurs; the country's portfolio of environmental degradation and capital stock at the point the optimal growth path is adopted will determine the system's eventual settling point. We find the threshold levels of capital and degradation for the competitive and socially optimal growth paths and therefore, derive the 'point of no return' for such economies.

The 'point of no return' is referred to as the Skiba point in the macro economics literature. It exists when there are non-linearities associated with the state variable, (for example, a concave-convex production function) thus leading to multiple history-dependent steady states (Skiba 1978, Tahvonen 1996). The Skiba point is the point from which one could go to either of the steady states and still get the same total welfare. However, when the number of state variables is more than one, it no longer remains a point but is a line or a plane as the dimensions increase. In the model described above, 'the point of no return' would actually be a line plotted on the capital-degradation plane. We derive this line by solving for combinations of capital and degradation in the socially optimal case, beyond which the system falls into the degraded steady state. This is represented below in figure 11. The two roughly vertical lines represent the points of no return for the competitive and the socially optimal cases, with the left one representing the competitive case.

INSERT FIGURE 11 HERE

Figure 12 shows the dynamics contained within the two Skiba lines. A competitive economy starting in the Skiba region, when left to itself, would eventually cross it and fall into the degraded state (case a, represented by diamonds heading out towards right from within the region contained by the two Skiba lines). If the regime change occurs after the region is crossed, the system still heads towards the degraded state (case b, represented by boxes heading out towards the degraded state). On the other hand, when regime change happens inside the region the system shoots for the ‘pristine’ steady state (case c, represented by stars heading out towards the pristine state).

INSERT FIGURE 12 HERE

At the point of regime shift, countries could be characterized by several possible combinations of environmental degradation and capital endowments. The low capital and low degradation characterizes an agrarian economy. High initial capital and low degradation is highly unlikely but is possible if the country has a competitive advantage in providing services or has geographical advantages. Similarly the case of high initial capital and high degradation may represent currently industrializing economies with low environmental preferences. Finally, the case of high initial degradation combined with low capital characterizes those countries that had rich mineral wealth but were unable to exploit it to build capital; however, the mineral extraction did have an adverse impact on the environment (Porter’s hypothesis).

Tunneling

From the above analysis it is clear that there may not exist a tunnel out of the EKC relationship that would help the society attain both high levels of capital and environment. However, the possibility of pollution-reducing technological advances, the likelihood of which is significant, has been in the ignored in the above formulation. Some theoretical models do incorporate such possibilities. Stokey (1998) proposes that pollution-efficient capital could only be used once a threshold level of capital has been crossed. This leads to a V-shaped environmental Kuznets curve. In this section we look at such threshold effects. We model the advent of pollution-efficient technology by the level of capital crossing some exogenously specified threshold, which is known. This threshold is characterized by a downward jump in the pollution function. The new pollution equation is given by:

$$(17) \qquad p = \beta k^{\alpha-\gamma} - \frac{a_1 k^{a_2}}{k^{a_2} + a_3}$$

The first term remains the same as previously specified. The second term incorporates the jump effect (which is similar to the hysteresis effect of the degradation function). Once the level of capital crosses this threshold, pollution shows a downward shift but still continues to rise with capital. By using the right combination of parameters, it could be shown that optimal capital accumulation in the socially optimal case involves a non-monotonic path for environmental quality as capital accumulates. In the initial stages of capital build-up, environment is degraded as emphasis is on reaching that pollution-reducing threshold, however, once the threshold is reached, the impact of reduced pollution helps bring the environmental quality back into a pristine state. This is shown in the figure below.

INSERT FIGURE 13 HERE

Conclusion

In this paper we presented a simplified theoretical model that incorporated the hysteresis effects associated with pollution accumulation into the theory of the environmental Kuznets curve. We showed that the stress on rapid capital accumulation without any concern for the stock effects associated with environmental pollution may lead to costly irreversibilities and hysteresis. Incorporation of these concerns, however, significantly lowers the desirable stock of steady state capital.

The model also indicates that a country need not start on the socially optimal growth path to ultimately reach the socially desirable levels of capital and environmental quality. It may be possible to reach the socially optimal state as long the threshold combinations of capital and degradation are not crossed. Further, the amount of effort required in terms of forgone consumption (or the rates of capital accumulation) depends upon a combination of various parameters. Significant amongst them are the initial levels of degradation and capital, the regenerative capacity of the environment, the levels of hysteresis, etc.

The proposed idea of ‘tunneling’ assumes that some transition path could be designed that would enable high levels of capital accumulation and still preserve the environment. However, we discovered that preserving the ‘pristine’ state comes only at a cost of reduced levels of capital accumulation. This is reflected in the large difference associated with the steady state capital levels with and without the regard for environmental degradation. Perhaps ‘tunneling’ may be feasible in the wake of significant future advances in pollution reducing technologies or geo-engineering advances that may help restore ‘degraded’ ecosystems at reduced costs. This raises additional questions about when to jump onto the socially optimal capital accumulation path when there may be expectations of such future discoveries.

It is also possible to explain some of the observed discrepancies in the literature on EKC from our analysis. One reason an EKC may not be observed in some cases is that even though there may exist a relationship between pollution levels and income, the observable indicators of environmental quality may still keep degrading due to stock effects. A simple example is the case of diminishing biodiversity all over the world. The existence of EKC, in such cases, then depends upon the type of environmental indicators chosen.

Finally, when one considers the stock effects of environmental pollution, a distinction has to be made between national and trans-national impacts. The above analysis is more representative of regional impacts such as eutrophication of lakes or loss of wetlands than global impacts such as carbon stock accumulation. The implications for capital accumulation may differ significantly in the two cases, however. At a country level, high levels of capital could be accumulated as effects of environmental degradation may not be immediate or may be dissipated, or may simply be unknown. The implications for capital accumulation at a global level are much harder to figure out due the complex inter-linkages between global economy, earth’s limited resources and fragile ecological balance. This significantly affects the preferences of the currently industrialized nations as it would have to include those of the industrializing ones. The impacts of global warming are not only direct (e.g. a rise in a sea level and loss of earth's biodiversity) but also indirect (spread of vector borne diseases and invasive species due to a change in climate pattern). As a consequence, impacts of industrialization can no longer be considered in isolation with the rest of the world. Therefore, at a global level, it may be much harder to find a 'tunnel' out of the 'spaceship'.

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Table 1: Parameters

α	η	ρ	$d0$	n	β	γ	δ	a	θ	r	b
.4	.25	.08	100	6	15	.005	.01	1	.001	.05	.8

Figure 1: Optimal Steady State Relation between Capital and Environmental Degradation

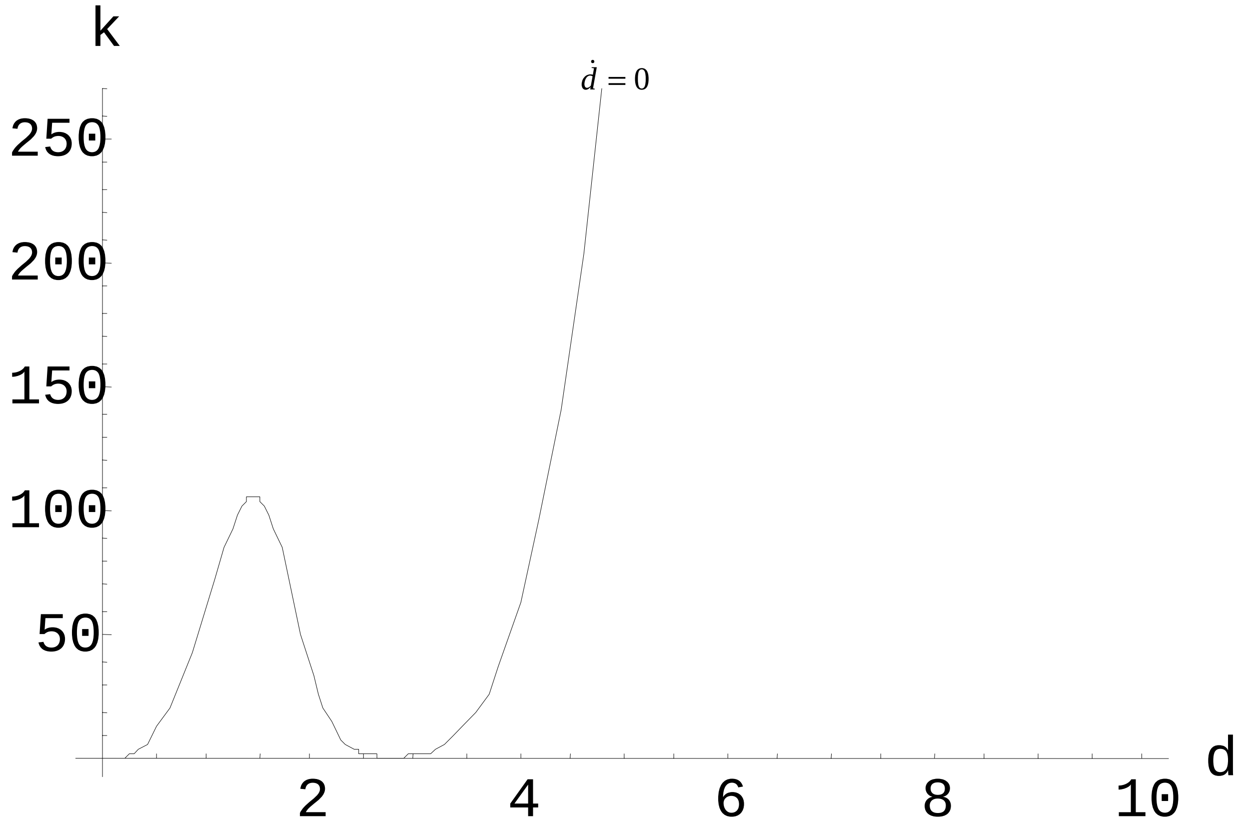

Figure 2: Shadow Price of Degradation

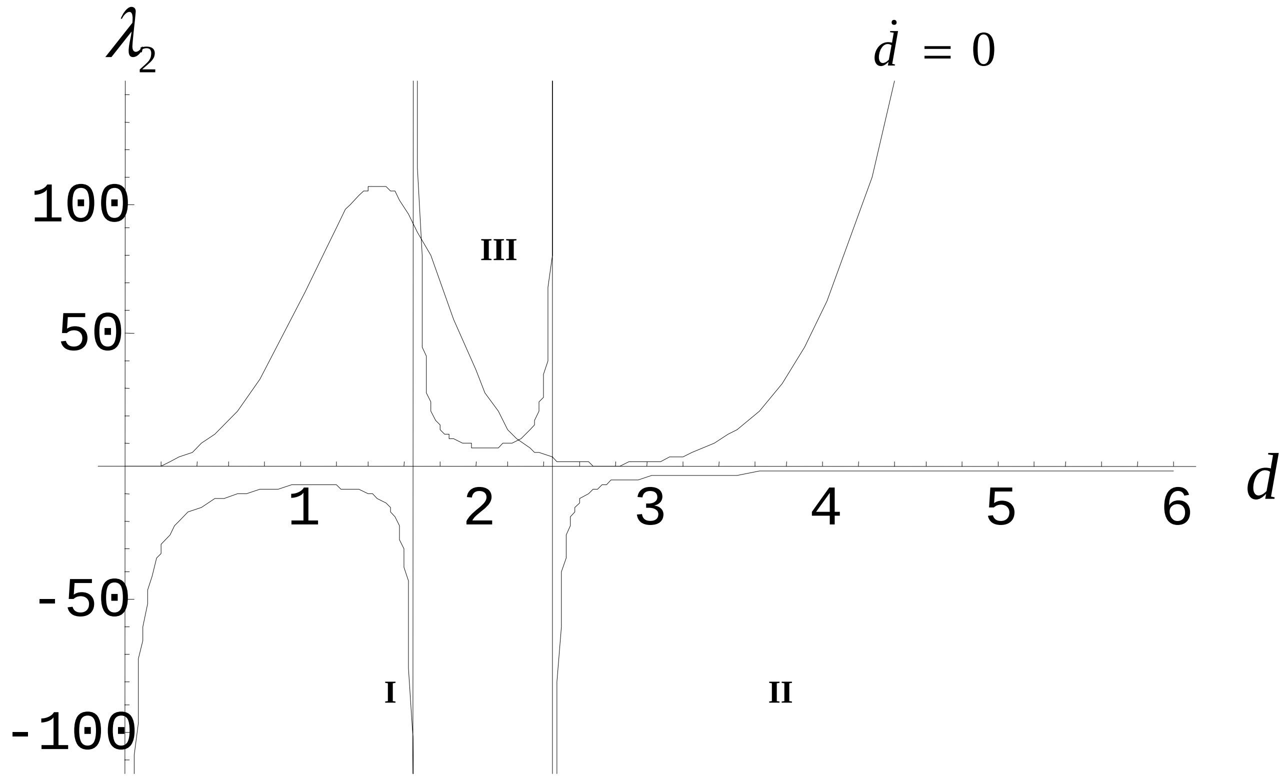

Figure 3: Relationship between pollution and degradation in steady state

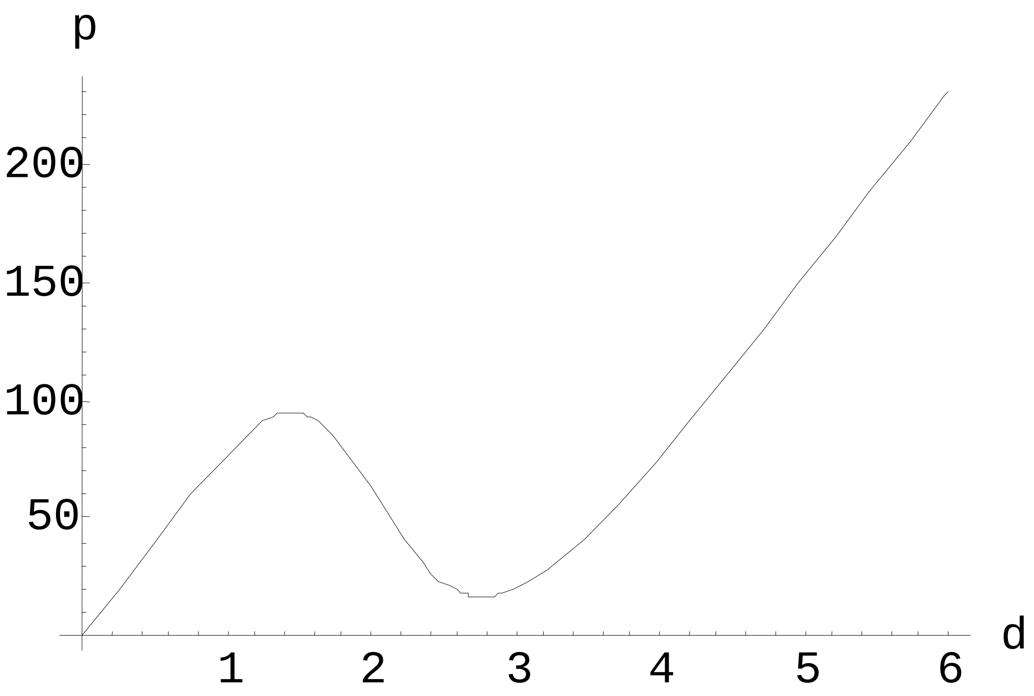

Figure 4: Relationship between consumption and degradation in steady state:

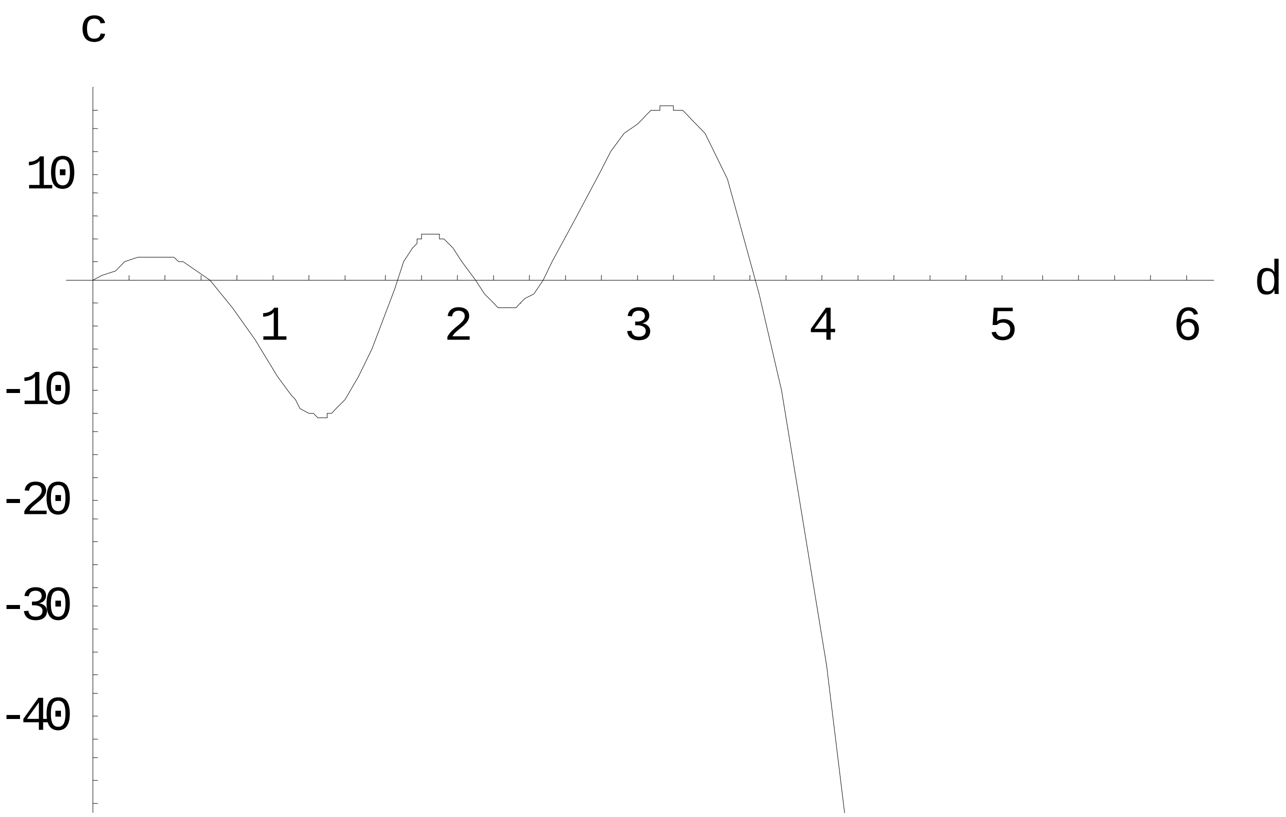

Figure 5: Socially Optimal Equilibrium

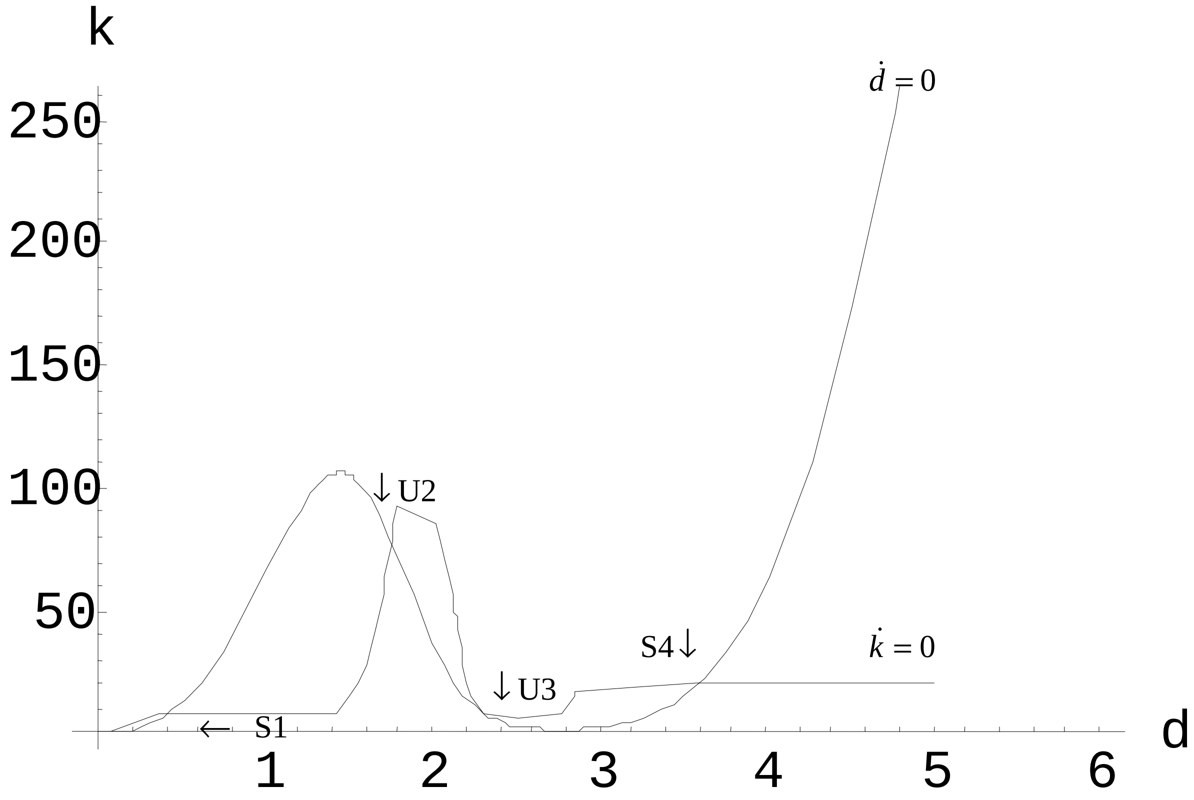

Figure 6: Socially Optimum Case

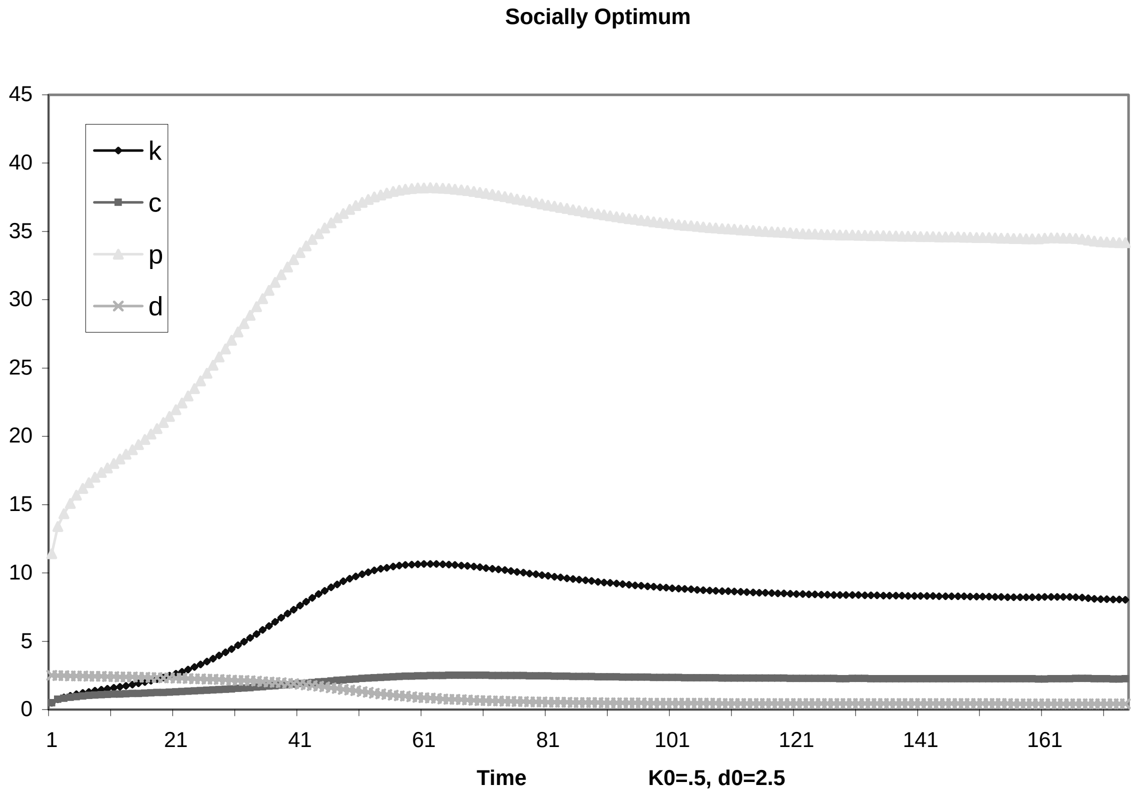

Figure 7: Comparison of Socially Optimum and Competitive Equilibrium

Cases

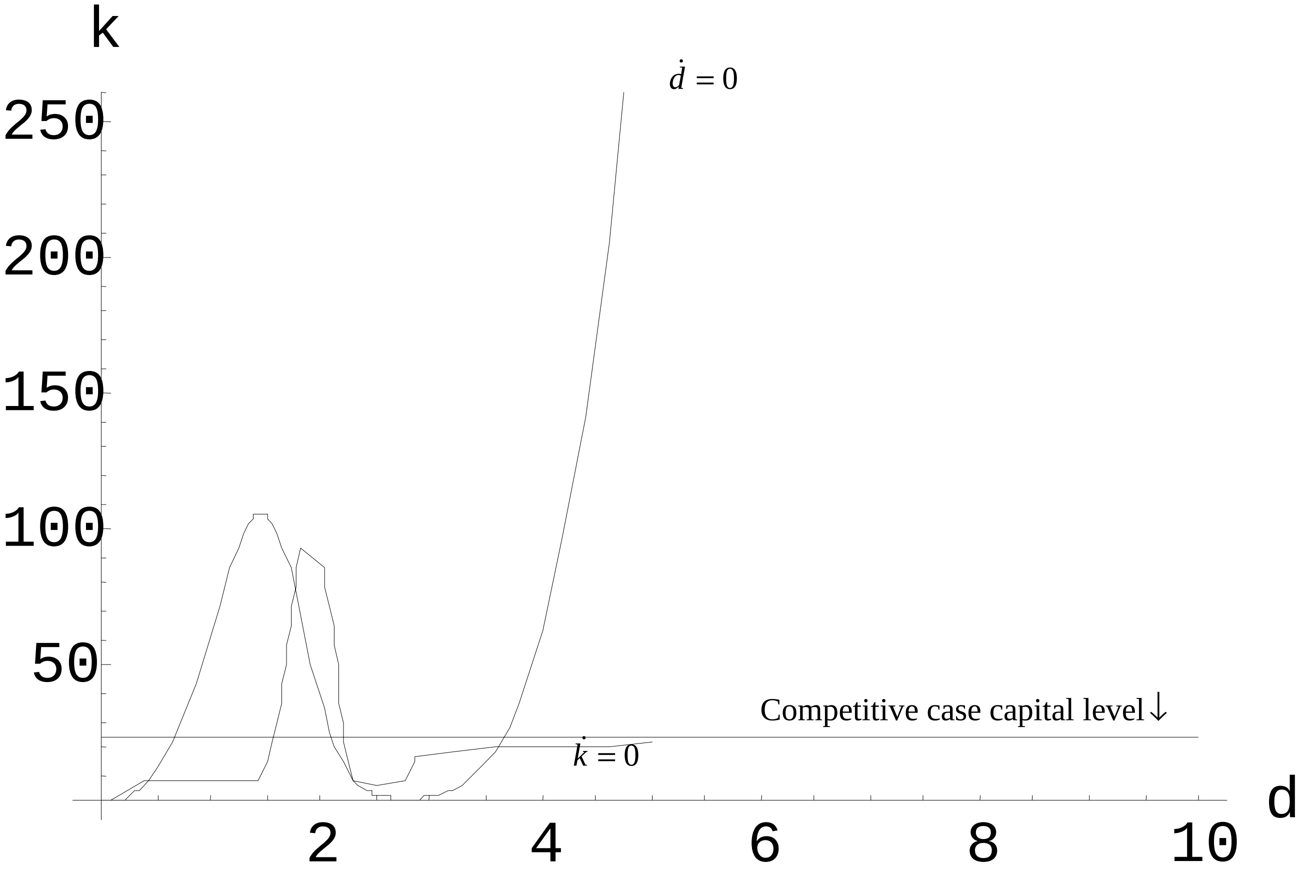

Figure 8: Competitive Case

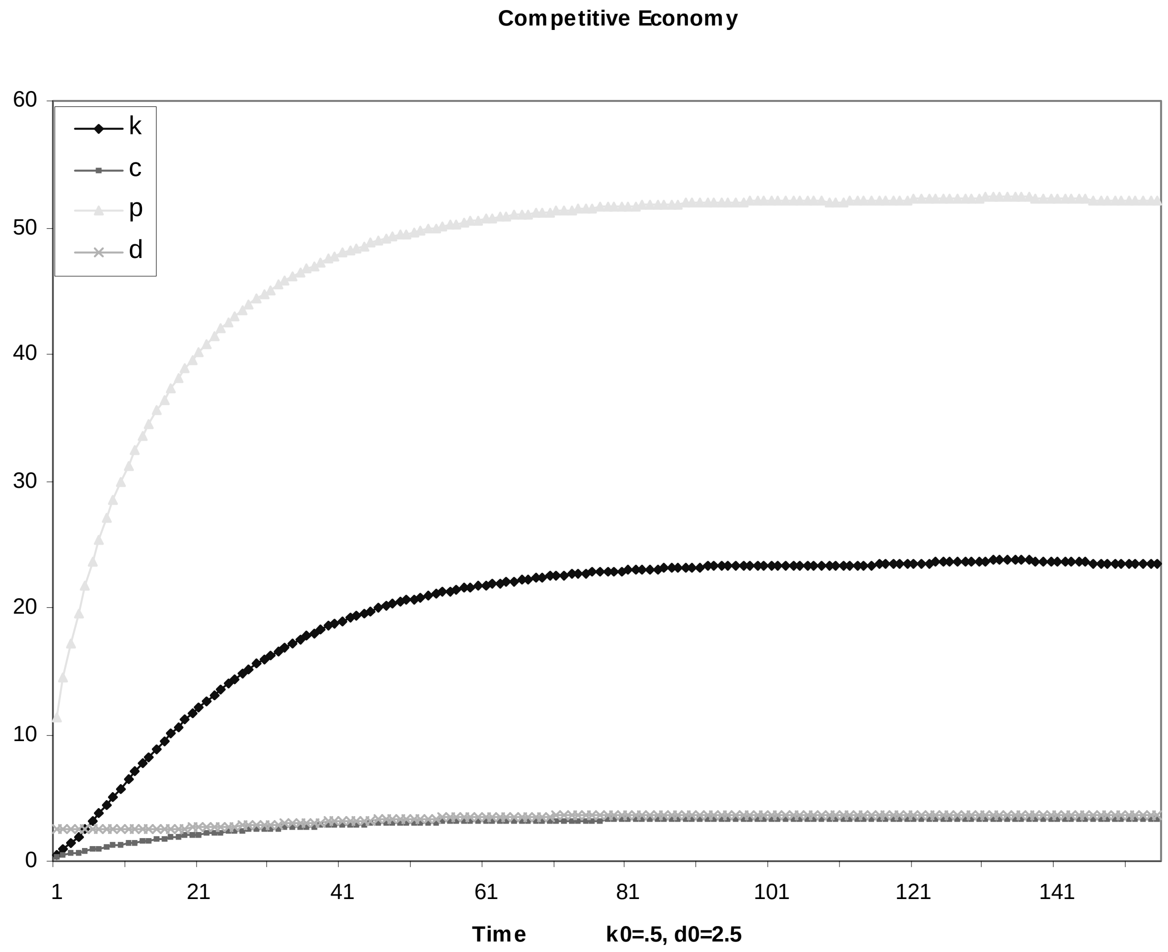

Figure 9: Degradation

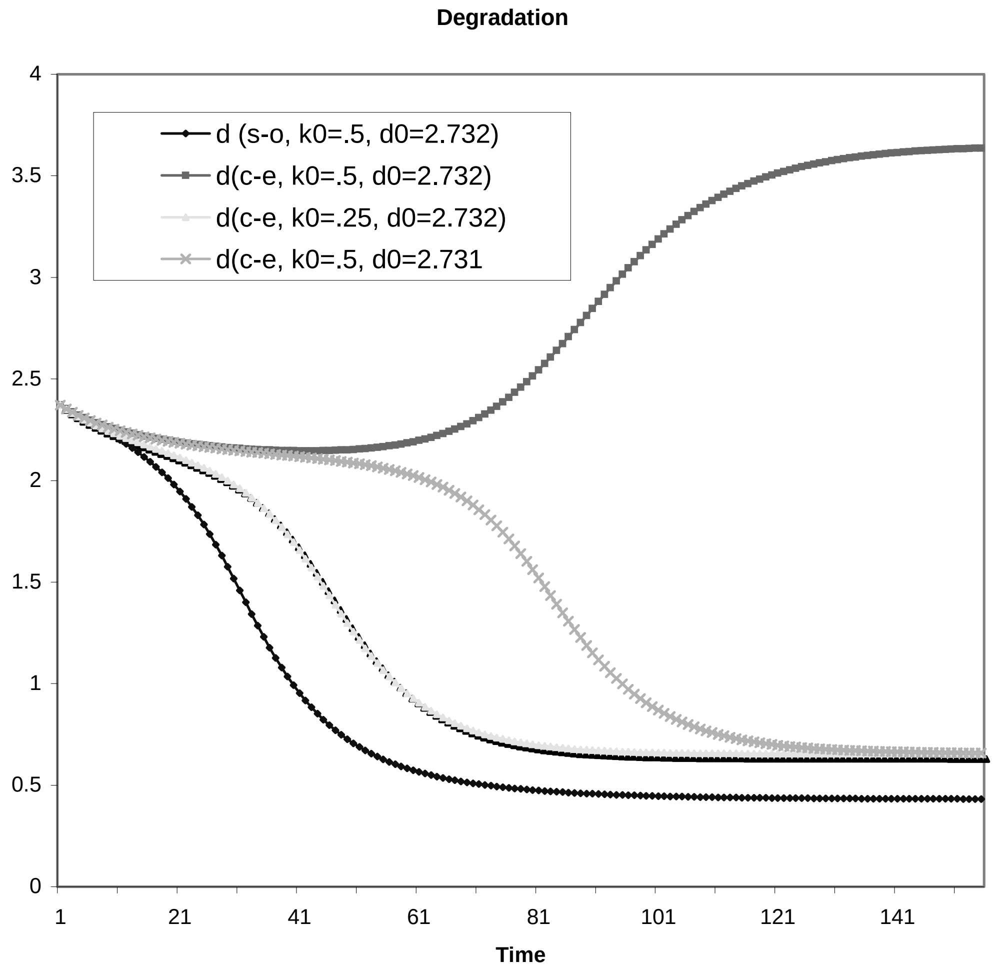

Figure 10: Capital

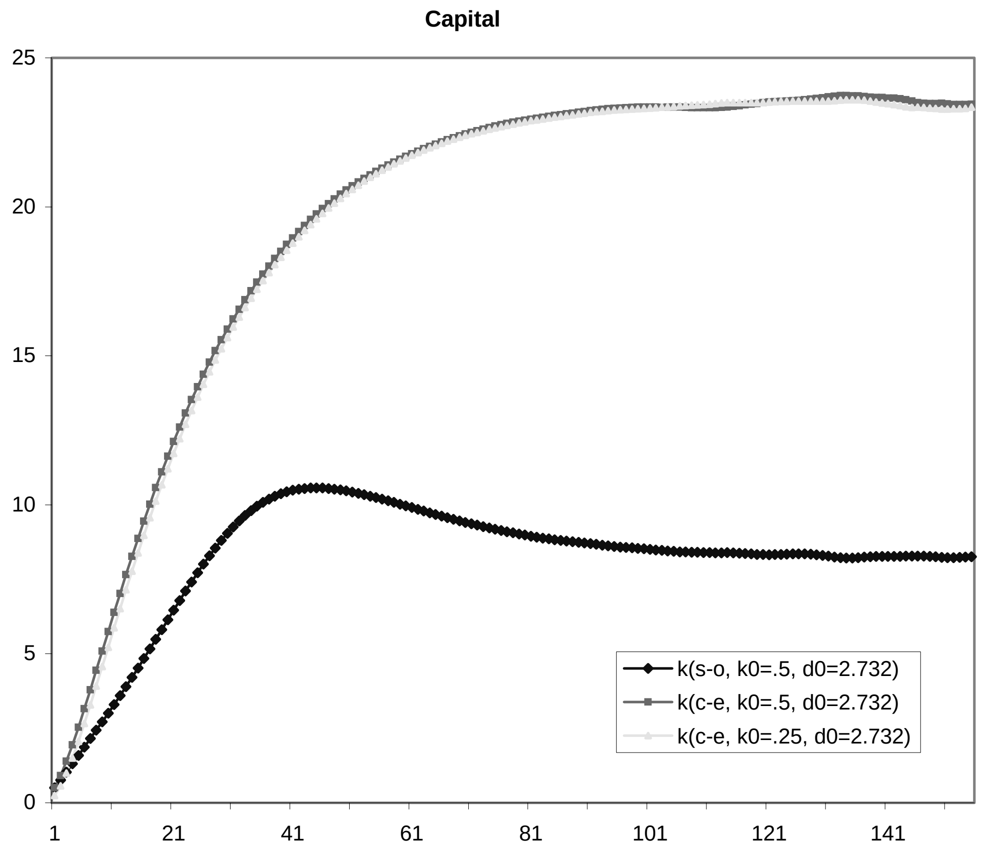

Figure 11: Point of No Return in the Competitive and Socially Optimal Cases

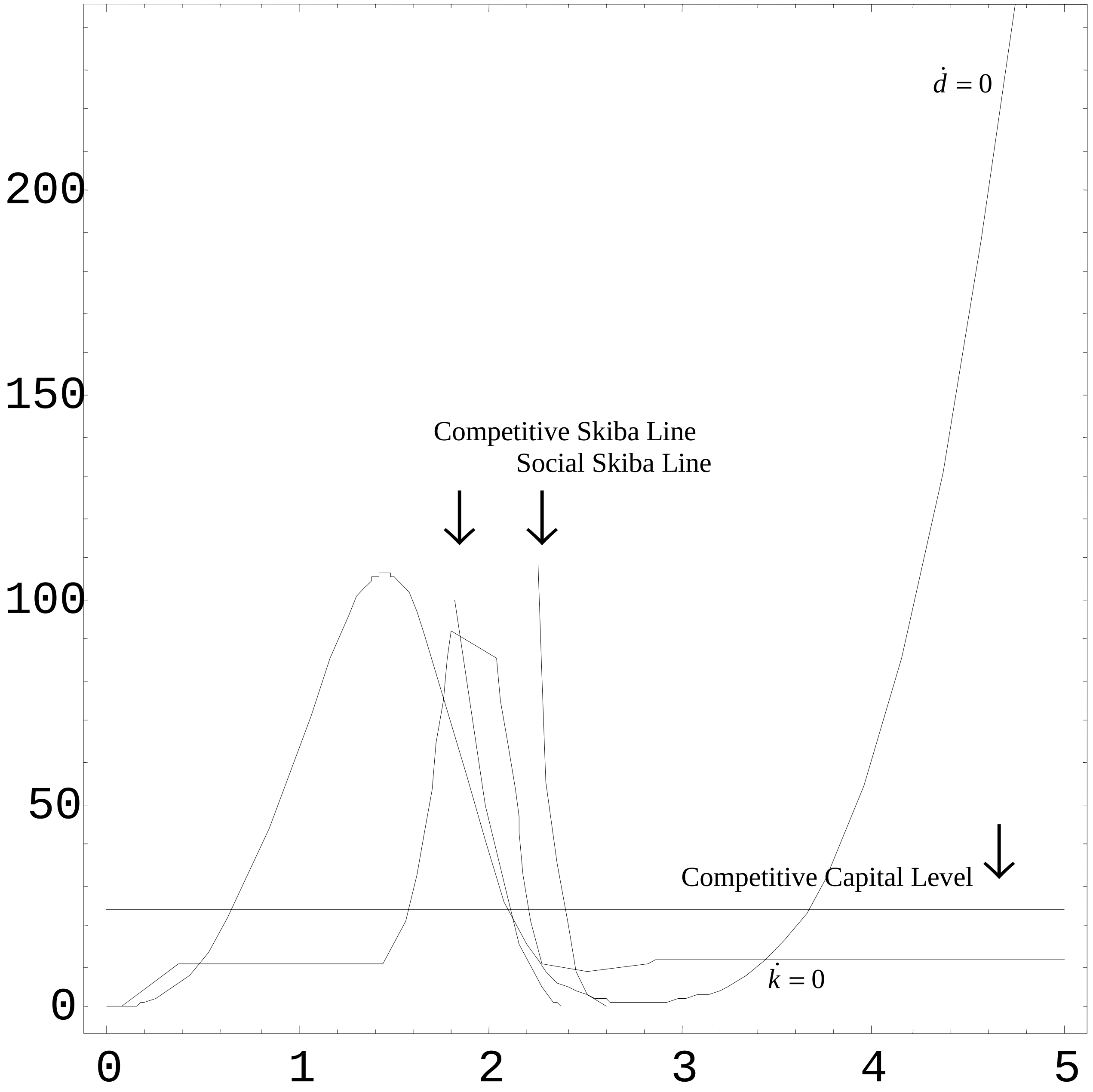

Figure 12: Dynamics within the Skiba Region

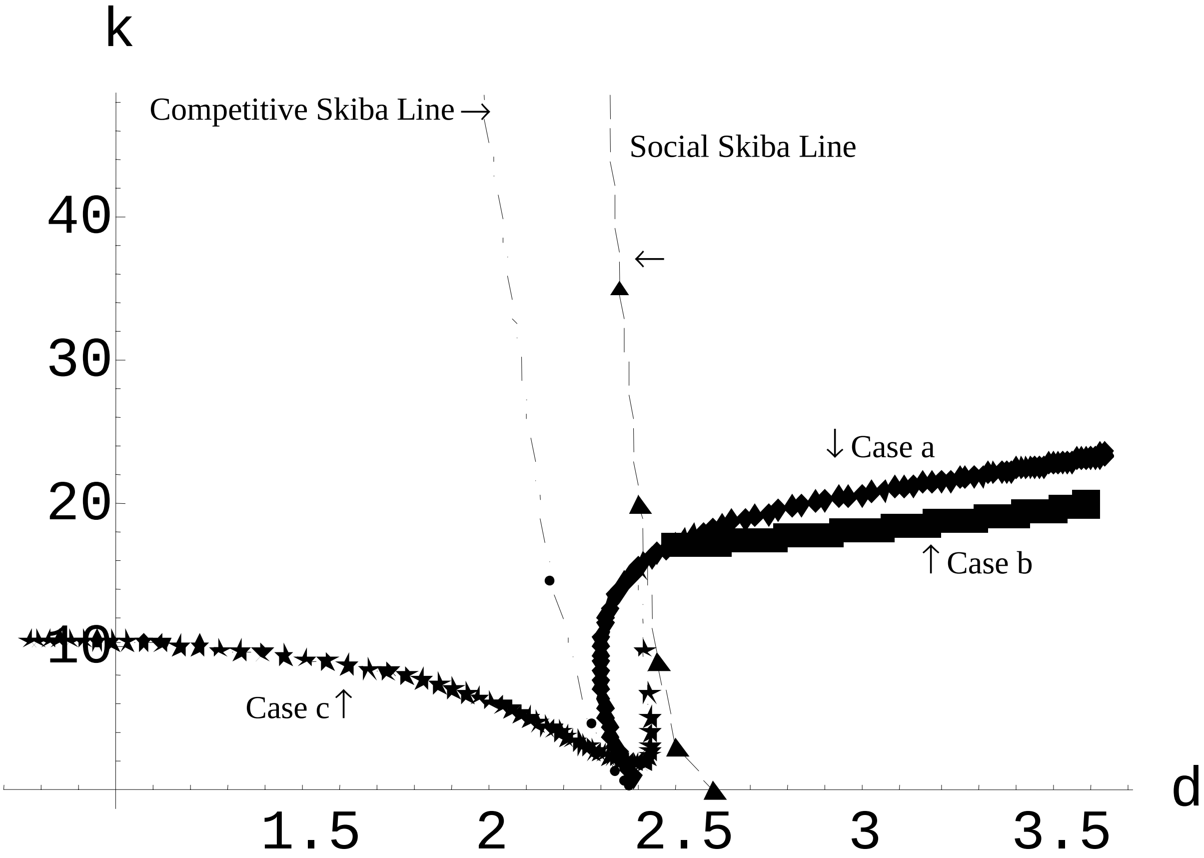

Figure 13: Tunnel