Achieving Economic and Ecological Resilience through Natural Resources

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Abstract

This paper explores the nature and role of inter-linkages between ecological and economic resilience in small scale economies towards maintaining long term sustainability. Positive inter-linkages could lead to beneficial co-evolution of the economy and ecology. However, in certain cases economic growth can only come at the cost of environment and might lead to its unsustainable exploitation. It is shown that initial conditions related to environment and capital could be crucial factors in determining a successful co-evolution of the environment and the economy. When natural hazards pose risks of environmental destruction, the rate of capital accumulation could increase or decrease depending upon the relation of such risks with environmental and capital stocks.

Keywords: Economic-Ecological Resilience, Natural hazards, Small scale economies

1. Introduction

Natural resources provide the basis for both ecological and economic support to society. The ecological services provided by natural resources are indispensable and often extend beyond regional boundaries. However, the economic support provided by natural resources is most directly availed to by people living in the immediate proximity of such resources. This is especially true for small scale economies (SSEs) where the livelihood of the entire population is dependent upon such open-access natural resources. In such cases there may emerge a conflict between providing ecological services at a societal level and livelihood services at a local level, if the existing historic balance between the two is disturbed. While the ecological services of forestry may extend beyond the local regions, the sustenance provided by forestry is limited to the immediate population. Historically, these objectives have been successfully met primarily due to the sustenance life style of the population dependent upon such resources. Over time however, the increasing reliance upon natural resources for economic gains stimulated by outside trade opportunities has caused significant shocks to these ecological regions and their surrounding SSEs. These disturbances in the ecological and economic realms warrant a second look at the previously un-disturbed historical balance between nature and humans and force the issue of whether such an equilibrium could be maintained where both economic and ecological services are provided at a larger scale. One crucial question is over whether these SSEs would be able to transform themselves into economically advanced societies without destroying the ecological environment in which they live. Another equally important question is over to what extent the historic balance of these SSEs is resilient from both ecological and economic shocks, which could be either external or man-made. Finally, if there is a linkage between ecological and economic resilience, what is its nature and sensitivity to disturbance? The current literature on these issues provides few insights to guide us through these questions. Adger et al. (2005) discuss the linkages between social and ecological resilience from coastal disasters. Folke (2006) discusses the role of behavioral responses towards brining socio-ecological balance. Socially determined habits could play a crucial role in maintaining delicate equilibriums of environment and economy simultaneously. Folke further argues that economic development leads to erosion of ecological resilience and thus could cause ecological surprises. Other inter-linkages between social and ecological systems that could provide sustainability have been discussed in Berkes and Folke (1998).

In this paper we limit our attention to the delicate interplay between ecological and economic resilience without delving into the human traditions that help maintain such balances. Consequently, we first design a conceptual model of resilience inter-linkages and then explore the above issues through theoretical analysis and numerical simulations that mimic plausible scenarios to derive the implications for long term sustainability.

We model economic and ecological linkages of socio-eco systems through the use of resilience analysis where threshold levels of environmental and economic capital stock are crucial in determining the successful transition of SSEs towards greater economic development, without compromising on the larger scale ecological services. We assume that while the SSEs are faced with a critical transitional barrier in terms of capital accumulation, the ecological systems could exhibit resilience too. For instance, if an SSE has maintained high levels of environmental stock, further increases in such stock would lead to resilience through which it may be able to enjoy even higher levels of environmental benefits. Whereas, if the environmental stock falls short of this critical threshold, then any man-made or natural disturbances might threaten the sustainability of such economies. However, with proper planning, it may be possible to initially restore the degraded environment and exploit higher environmental and economic rewards later on through ecological resilience.

Capital accumulation is possible through the harvesting of the environmental stock and exhibits resilience in the sense that once a threshold level of capital has been crossed, it expands rapidly. This is because a higher capital stock makes it much more efficient to meet the demands of the outside world through large scale conversion and transport of ecological goods.

The ecological and environmental resilience effects together present possibilities for sustainable development if judicious use of resources is made over time. However, the rate of capital extraction, consumption and harvesting become key factors in determining sustainability, along with the nature and extent of the resilience effects. The findings this paper confirm that environmental and economic thresholds play a key role in determining whether or not a highly sustainable equilibrium could be attained which could be beneficial at both local and societal levels. Starting values of stocks of environmental and economic capital play a crucial role in determining whether the equilibrium attained would be that of a high level of capital and environmental stock type or not. Weights on the welfare function, that comprises benefits from the environment, benefits from harvesting and capital accumulation, are crucial in leading to a sustainable equilibrium. The nature and extent of resilience linkages play an important role in this equilibrium too. Finally, when risks to the environmental resources exist through natural hazards, important implications arise for time path of capital accumulation.

2. Model

The approach in this paper assumes ecological and economic resilience as being inter-linked and capable of providing positive feedbacks to each other.[1] The extent and direction of the feedback depends upon the various combinations of environmental stock and the capital stock that exist at any point of time. The rate of capital accumulation is determined by the stock of environment. Ecological resilience is measured as a rightward shift in the relationship between environmental stock and the amount that could be harvested to keep the stock at a constant level. This relationship is defined in equation (1) below:

$$(1) \qquad \dot{q} = \eta \frac{q^a}{q^a + b} - \delta q - \alpha h .$$

The environmental stock (q) growth gets positive feedbacks from its own stock levels, but is reduced through a natural rate of decay δ and any external harvesting at the rate α .

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[1] Conventionally, resilience has been defined in two ways in the ecology literature. First one, termed as the '*engineering resilience*' defines it as the speed of bouncing back of any perturbed system (Pimm 1984). The other, termed the '*ecological resilience*', is about the amount of stress that the system can tolerate before flipping from its original state to another stable but degraded state (Holling 1995, Carpenter and Cottingham 1997). In certain cases a system might both be *resistant* and *resilient* to external shocks. *Resistance* in the literature is defined as the ability of the system to sustain a shock while remaining unchanged, as compared to resilience, which refers to its ability to revert back to the original state.

In this formulation of environmental stock dynamics we assume that the stock does not behave like a renewable resource (say a fishery growing at a logistic rate) which could be harvested at a certain sustainable level. Instead, the assumption is that any harvesting of the resources only reduces the stock of environmental capital by a fraction of the amount harvested. This type of growth function assumption is more suitable for situations where natural resources provide periodic consumptive resources, such as fruits and vegetables, which could be either consumed or sold in the market, keeping the stock of resource more or less constant[2]. The idea is that these societies rely on forest products for sustenance; however, they could accumulate capital at a faster rate by reducing the forest stock. When forest stock is reduced through harvesting, the value of the α would be close to 1.

The capital stock growth rate is determined by:

$$(2) \qquad \dot{k} = \beta h + \eta \frac{k^a}{k^a + b} - \theta k + rk \ .$$

Capital is built up through harvesting of natural resources at the rate β, net of depreciation θ and also accrues an interest on its stock at the rate r. An example of capital stock accumulation through natural resources would be chopping down trees to build boats or other products that could be exchanged in the outside market for money. The exact nature of accumulated here is left undefined to allow for accumulation of both financial and productive assets. The proportion of the harvest which is not converted into capital is available for consumption.

Now we can look at the steady state relationships governing environmental and capital stocks with respect to harvesting. Equation (1), in steady state, can be written as:

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[2] The appendix details some of the parameter values for a graphical exposition.

(3) $$h = \frac{\eta \dfrac{q^a}{q^a + b} - \delta q}{\alpha}.$$

Equation (2), in the steady state, can be written as:

(4) $$h = \frac{-\eta \dfrac{k^a}{k^a + b} + \theta k - rk}{\beta}.$$

Equations (3) and (4) determine the steady state relationship between environmental stock and capital. For base case parameter values, as mentioned in the Appendix, we could plot the steady state relationship between harvest and environmental stock as shown in figure 1 below.

INSERT FIGURE 1 HERE

In the above figure, a high rate of harvest could only be maintained at a higher level of environmental stock. In figure 2 below, the relationship between harvest and capital stock turns out to be negative for a certain range of capital, implying the significance of the resilience effect.

INSERT FIGURE 2 HERE

Figure three shows the two graphs together.

INSERT FIGURE 3 HERE

Note that the x-axis in the above figure represents both capital and environmental stock. It is possible for the SSEs to achieve multiple equilibria based upon the initial stocks of environment and capital. The possible of multiple equilibriums arises judging from the non-linear steady state relationships as shown above. The crucial question is then, how could these SSEs attain the better equilibrium where both environmental and capital stocks are higher. Given the above states of motion for environment and capital, we explore a social optimization problem as defined below:

$$(5) \qquad max\int_0^\infty (w_q q + w_h(1-\beta)h^\gamma + w_k k)e^{-\rho t}dt\,,$$

subject to the constraints (1) and (2). The welfare function as given by equation (5) incorporates the value from environmental stock (*q*) socially weighted by parameter w_q, weighted utility from the portion of environmental harvest which is consumed, $w_h(1-\beta)h^\gamma$, and the utility from capital stock weighted by w_k. The social planner optimizes over these three weighted objectives subject to the constraints posed by the equations of motion of capital and environmental stock. The current value Hamiltonian is given as:

$$(6)\, w_q q + w_h(1-\beta)h^\gamma + w_k k + \zeta_1(\eta\frac{q^a}{q^a+b} - \delta q - \alpha h) + \zeta_2(\beta h + \eta\frac{k^a}{k^a+b} - \theta k + rk)\,.$$

The first order condition with respect to harvest gives:

$$(7) \qquad \gamma w_h(1-\beta)h^{\gamma-1} - \xi_1\alpha + \xi_2\beta = 0\,.$$

The no-arbitrage condition for environmental stock requires that the equation of motion for the shadow price of environmental stock evolve as:

$$(8) \qquad \dot{\xi}_1 = -w_q + (-\partial\frac{\eta\frac{q^a}{q^a+b}}{\partial q} + \delta + \rho)\xi_1\,.$$

Similarly, the shadow price of stock of capital evolves as:

$$(9) \qquad \dot{\xi}_2 = (-\partial\frac{\eta\frac{k^a}{k^a+b}}{\partial q} + \theta - r + \rho)\xi_2 - w_k\,.$$

In steady state, equations (8) and (9) equate to zero, thus giving:

$$(10) \qquad \frac{w_q \Big/ \left(-\partial \frac{\eta \frac{q^a}{q^a + b}}{\partial q} + \delta + \rho\right)}{w_k \Big/ \left(-\partial \frac{\eta \frac{k^a}{k^a + b}}{\partial q} + \theta - r + \rho\right)} = \frac{\xi_1}{\xi_2}.$$

Equation (10) requires the discount-weighted ratio of the weights on environment to the weights on capital accumulation must equal the shadow price of the two in steady state. Notice that a marginal increase in the stocks of capital or the environment leads to an increase in the welfare by the weights assigned to them. Whereas, the shadow prices of these stocks is the cost of increasing those stocks which is measured in terms of forgone harvesting which is used for consumption. Therefore, the discounted value of the increase in welfare generated when summed up to infinity must equal the cost of increasing this stock marginally. Also, notice that the rate of change in the hysteresis effect with a marginal change in the stock, $\left(-\partial \frac{\eta \frac{q^a}{q^a + b}}{\partial q}\right)$, enters as a discount factor in the above equation. The implication of this is that with an increase in the marginal stock of capital or environment, the potential to cross the threshold increases, thereby, increasing the value of that stock. Because this term enters as negative in the denominator, it raises the value of that marginal increase in stock. Also, notice that the partial of the hysteresis impact with stock would be highest around the threshold and minimal away from it, thereby introducing a tendency in the optimization mechanism to reach to that threshold faster and might also determine whether or not a highly rewarding equilibrium is attained. It might be possible that costs and benefits of increasing the environmental and capital stocks are such that if the starting values of these stocks are very near this threshold a highly desirable equilibrium would easily be attained where both the stocks of capital and environment are enhanced. Whereas, when the starting values of capital and environmental endowments are not in close proximity of these thresholds, a lower equilibrium would be attained, where capital may be accumulated but at the cost of the environment. In order to confirm this intuition, we take recourse to numerical simulations in the next section. We explore some plausible scenarios that may lead to good or bad outcomes.

3. Numerical Simulations

The parameters used for numerical simulation are detailed in the Appendix. Figure 4 presents the time path of capital stock evolution under several scenarios. The base case (as described in Appendix) leads to a low stock of capital accumulation over time. When the rate of depreciation of capital, given by θ, is lowered to .1, there is a high level of capital accumulation. Capital accumulation is also higher when the initial environmental stock is higher (q_0=2) and the weight on the environment in the welfare function is increased to .5. The consequential environmental impacts from capital accumulation are shown in figure 5. A higher weight on the environment makes accumulation of capital consistent with a high level of environmental stock, but ironically, a lower depreciation rate of capital leads to a destruction of the environment. The utility function (figure 6) is higher under the high weight on environment scenario than the case when depreciation rate is lower. Also, note the non-linear jumps in the utility function which happen with a fall or rise in the environmental and capital stocks under (over) the resilience thresholds.

INSERT FIGURES 4, 5 and 6 HERE

Figure 7 depicts the non-linear relationship between the environment and the capital in the steady state. In order to explore the time paths of environmental and capital stock we perform some more simulations and impose the time paths on the steady state relationship as shown in figure 8.

INSERT FIGURES 7 and 8 HERE

Notice that when k_0 =. 3 and q_0=3, a lower steady state is reached. However, notice the high accumulation of environmental stock which is consumed periodically instead of being used for capital accumulation. This is because, given the combination of parameters and the higher weights in harvesting for consumption, it is not optimal to accumulate a high level of capital stock. Figure 9 plots the steady state relationship between environment and capital for a different set of parameter values where capital depreciation is lower.

INSERT FIGURE 9 HERE

Figure 10 shows higher levels of capital stock accumulation when the starting level of environmental stock is higher and the rate of depreciation of capital is lower.

INSERT FIGURE 10 HERE

Figure 11 depicts the importance of threshold values, as for the same parameters as used in figure 10, but with a lower level of environmental stock, the system gets stuck and neither of the resources is accumulated in the long run.

INSERT FIGURE 11 HERE

4. Natural Hazards and Economic-ecological Resilience

The equilibria attained in the above examples may not be sustainable in the long run if there are external threats to the environmental and economic resources, such as through coastal flooding. There is a real risk of resources getting decimated under these events and the risk might even be stock related. What are optimal policy options under these situations? Do stock-related risks warrant lower or higher realizations of these resources? In this section we briefly explore these issues. The planner's problem is now to optimize expected value under risk from a natural hazard and to decide whether and when to cross the resilience thresholds. The optimal control problem is re-defined as:

$$(11) \qquad \int_0^\infty (w_q q + w_h(1-\beta)h^\gamma + w_k k + \dot{\lambda}\frac{ke^{(r-\theta)}}{r-\theta})e^{-\lambda(t)}e^{-\rho t}dt \, .$$

In the above formulation there is a risk of coastal flooding that wipes out all natural resources and the inhabitants are left only with their accumulated capital, which they could take with them in the event of an impending disaster. The risk dynamics is characterized by an exponential distribution, the hazard rate of which is given as $\dot{\lambda}$. Upon realization of flooding, we assume that the resilience effect of the capital is lost and the inhabitants only derive the interest rate on it for the rest of its life span, until it gets depreciated. The value of this capital summed up to infinity is given as: $\frac{ke^{(r-\theta)}}{r-\theta}$. The planner's job, as before, is to allocate resources between various uses such that the expected welfare is maximized.

Figure 12 depicts the time path of capital accumulation when the initial levels of environment and capital are the same as in figure 10 ($q_0 = 4, k_0 = 1$). Because the risk of hazard increases with time, there is no point in accumulating too much environmental stock and capital is converted very fast at the cost of environment.

INSERT FIGURE 12 HERE

However, a more realistic situation would be where environmental stock actually reduces the damages from coastal flooding such as through resistance to flood waters offered through trees, etc. In this situation, the hazard rate is given as $\dot{\lambda}(q(t))$ and the objective function would involve optimizing over the original welfare function and a reduced welfare function that has the surviving environmental stock after the hazard. It is possible that under this situation a higher stock of environment is maintained thereby making the high equilibrium possible. However, the exact nature and time path of such an accumulation would be governed by the efficacy of environmental stock in reducing flooding damages and it ability to provide goods to the community after flooding.

5. Conclusion

The issue of deriving economic resilience through environmental resources is a very important one, especially as the threats posed to SSEs from global climate change related damages are increasingly becoming real. There is a need to understand the interdependence between these resources to manage the impact of natural hazards on these economies while simultaneously helping them move towards higher economic development. There are a number of factors that influence these inter-linkages and are often case-specific. However, this paper brings out some of the main factors that matter the most.

The results in this analysis highlight the role of understanding the nature of relationship between the environment and the economy in SSEs. When significant non-linearity exists, possibilities of positive feedbacks present good opportunities to achieve maintain a high level of sustainable development through proper management of resources. The risk of natural hazards significantly alters the optimization paths and the decisions over the extent of capital and environmental stock accumulation. Understanding the exact nature of relationship between the risk of natural hazards and their mitigation options is crucial for long term optimization and needs to be researched further. The weighting of the welfare function is also crucial in determining the nature of the equilibrium and highlights the role for outside intervention. Public intervention, when the historic equilibrium is disturbed by outside influences, becomes a key element towards deciding the fate of these SSEs.

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7. Appendix

Parameters of the Model

a	8	Hysteresis parameter
η_1	4	Hysteresis parameter for environment
η_2	1	Hysteresis parameter for capital
$b1$	10000	Hysteresis parameter for environment
$b2$	100	Hysteresis parameter for capital
Q_0	1	Initial level of environment
k_0	1	Initial level of capital
α	.5	Harvest efficiency parameter
β	.03	Conversion rate of harvest into capital
γ	1.2	Elasticity of utility with respect to consumption
θ	.3	Capital depreciation rate
δ	.01	Natural rate of environmental decay
ρ	.15	Rate of time preference
w_k	.25	Weight on capital
w_q	.25	Weight on environment
w_h	.5	Weight on consumption
r	.15	Rate of return on capital

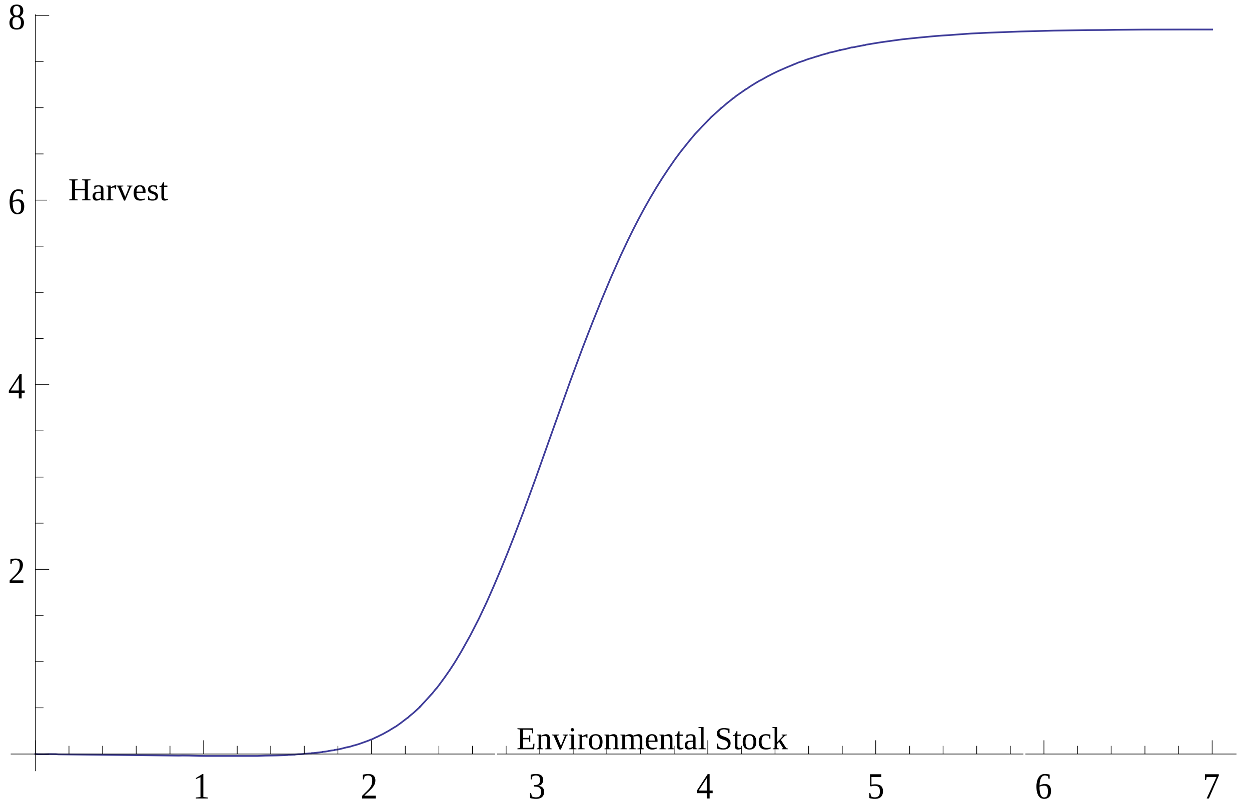

Figure 1: Steady State Relationship between Harvest and Environmental Stock

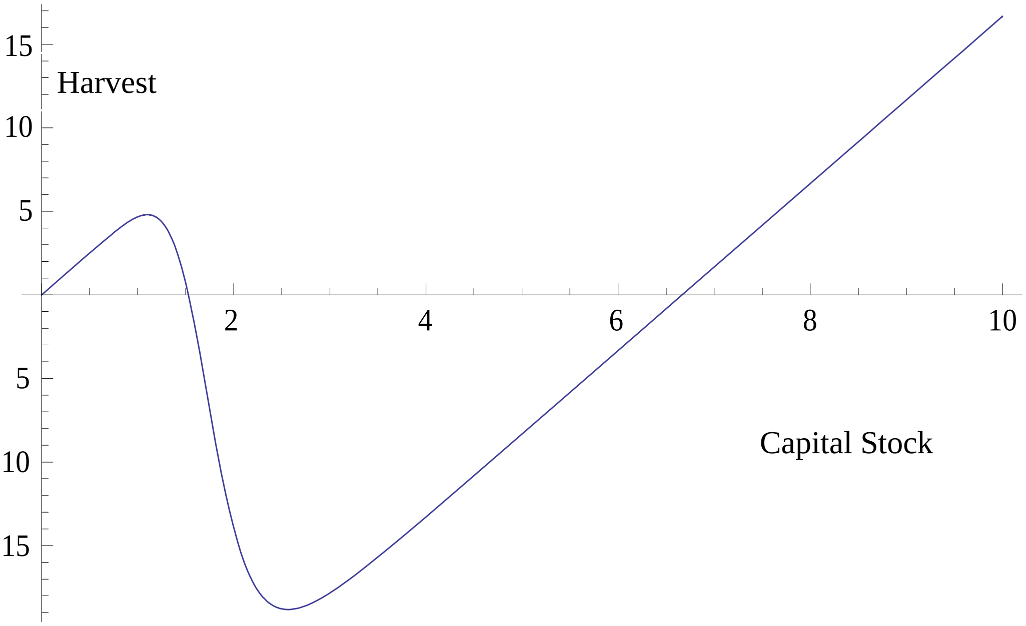

Figure 2: Steady State Relationship between Harvest and Capital

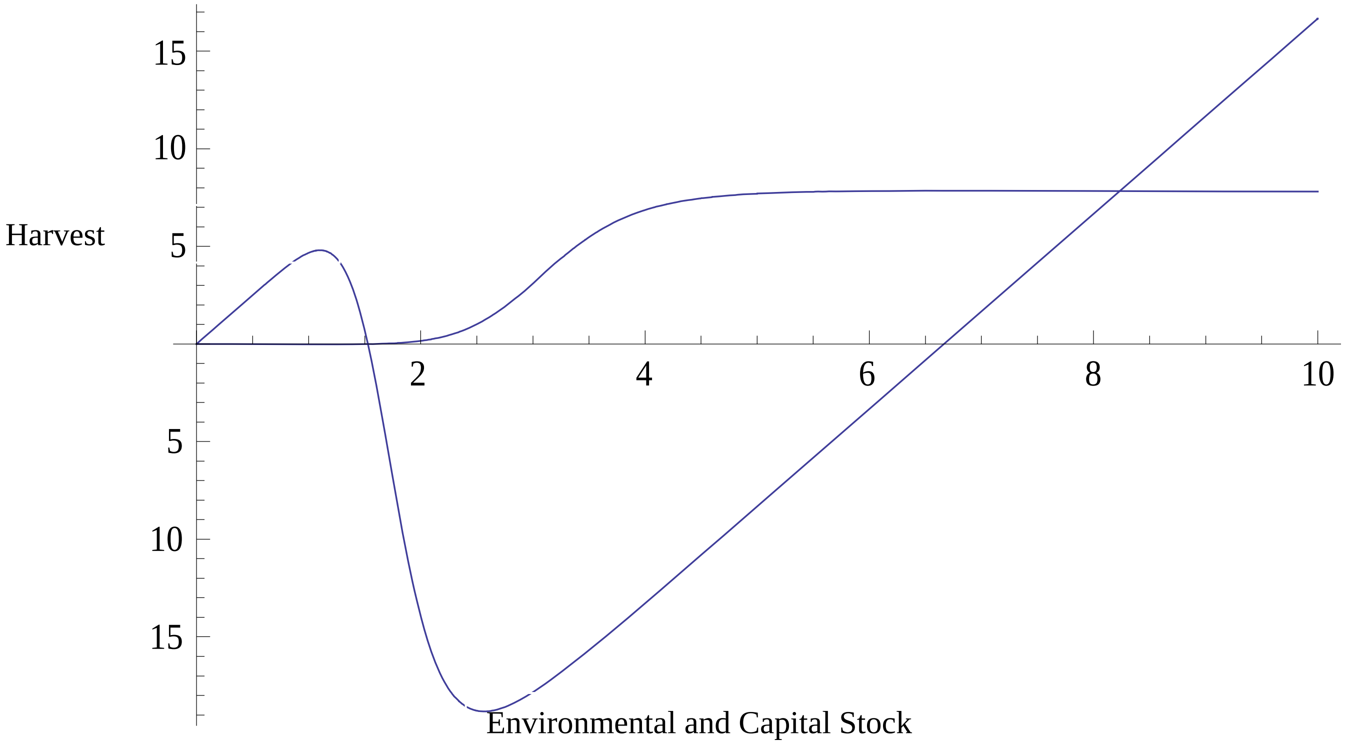

Figure 3: Steady State Relationship between Harvest and Stocks of Environment and Capital

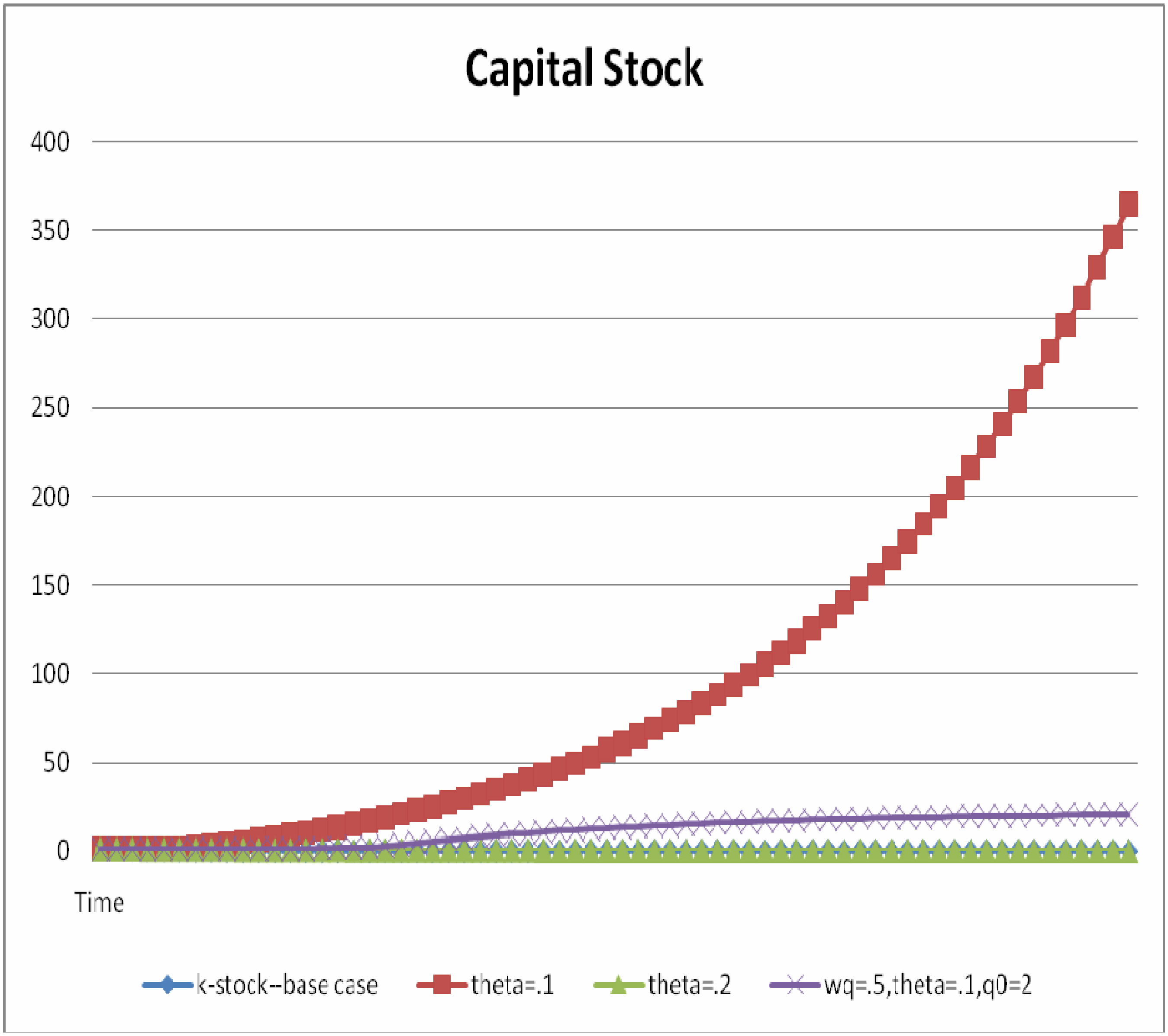

Figure 4: Captial Stock over Time

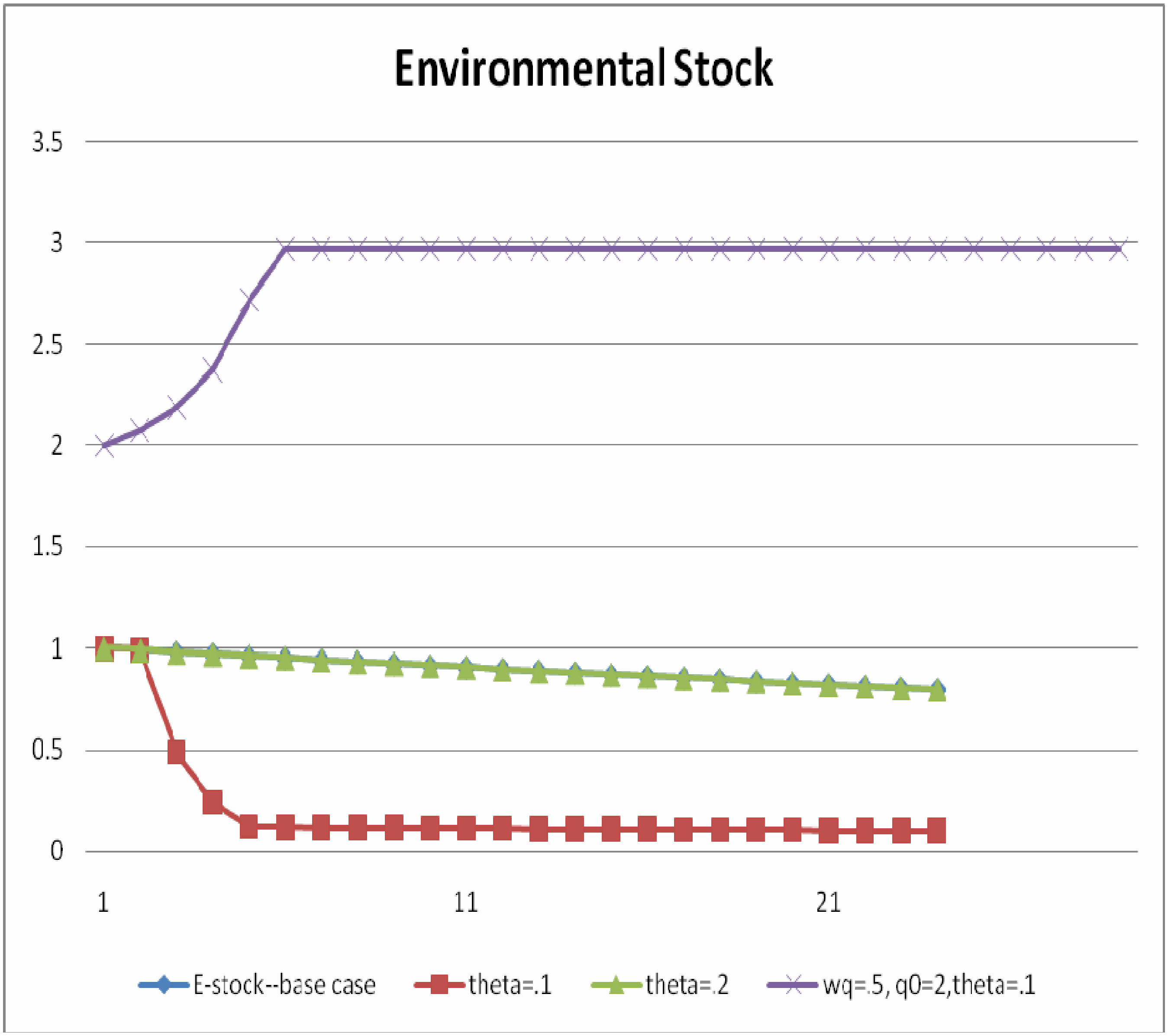

Figure 5: Environmental Stock over Time

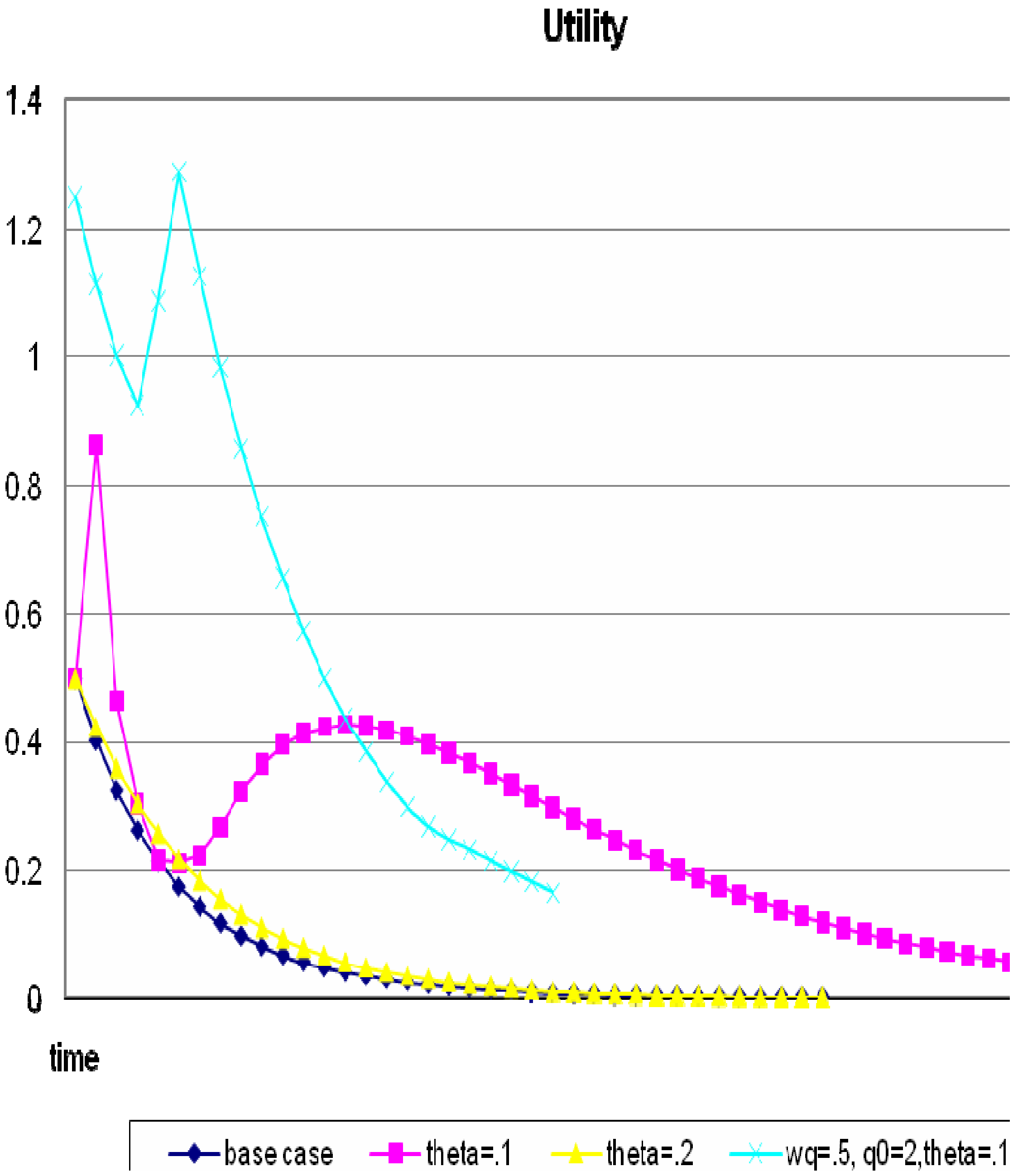

Figure 6: Utility over Time

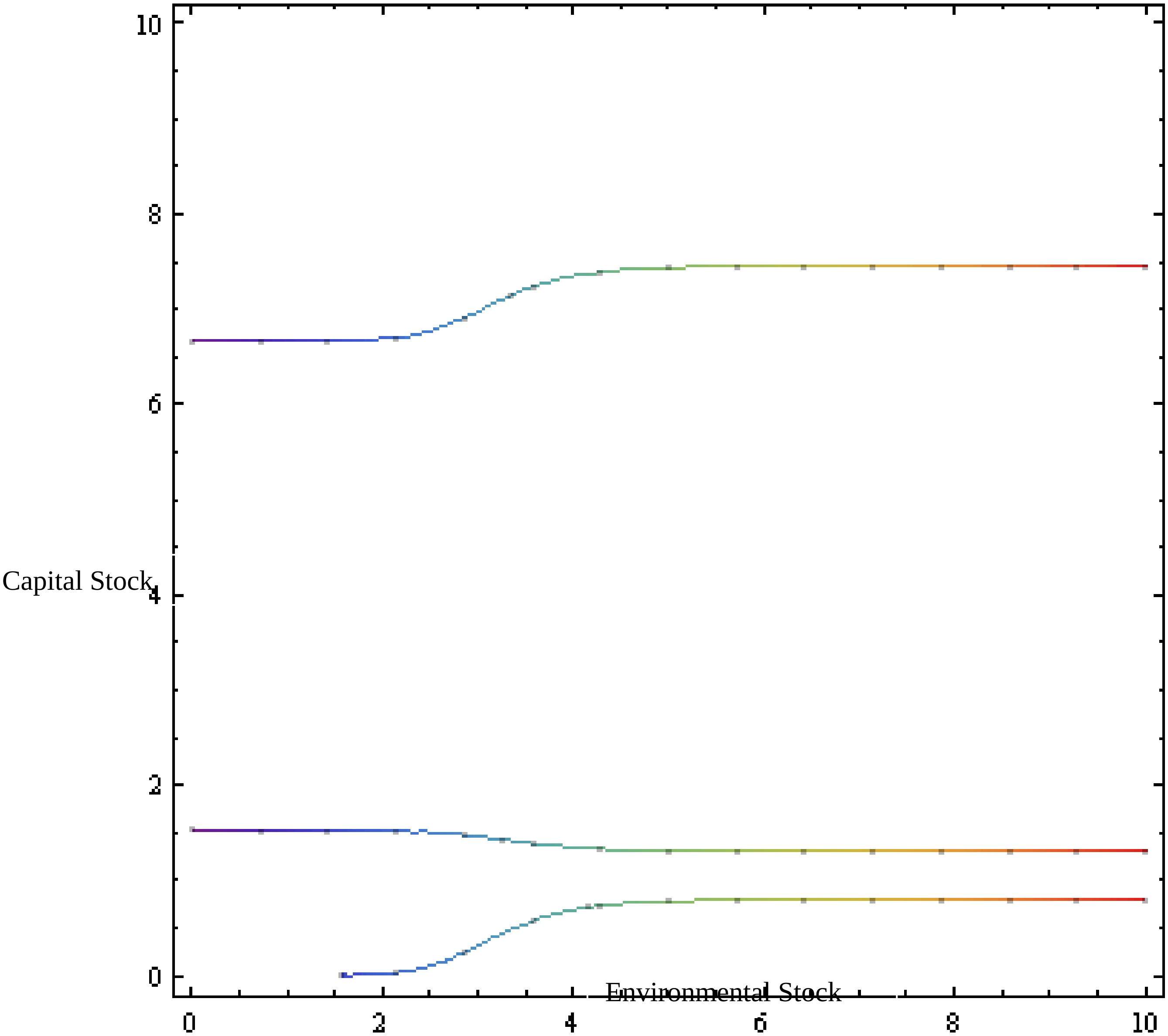

Figure 7: Isoclines for the steady state where $\dot{k}$ and $\dot{q}$ are zero.

Note: α =1; β =.05; a =8; b1=10000; b2=100; η_1 =4; η_2 =1; δ =.01; θ =.3; r=.15

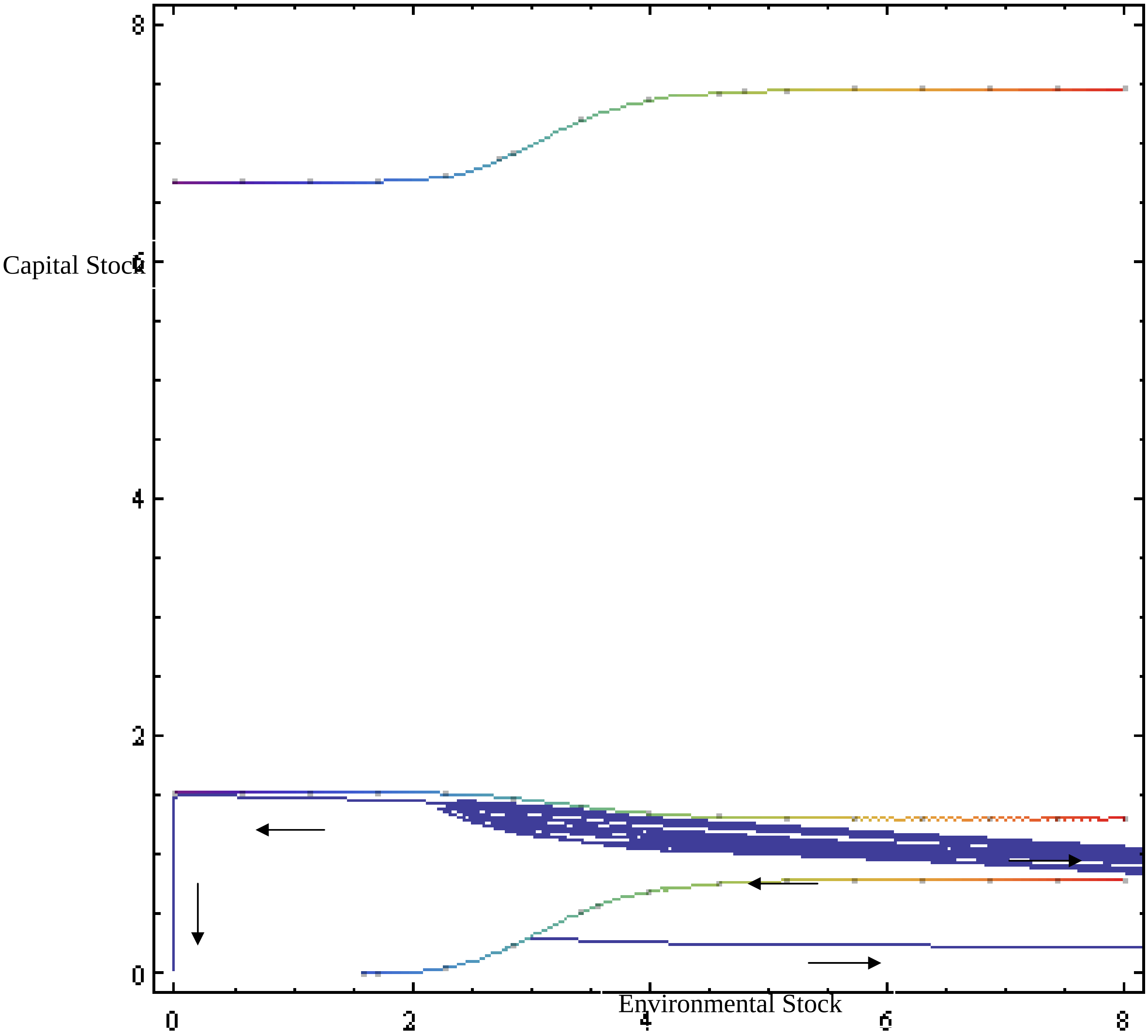

Figure 8: Time path of q and k when a Higher Steady State is reached
Note: q /3/, k /.3/

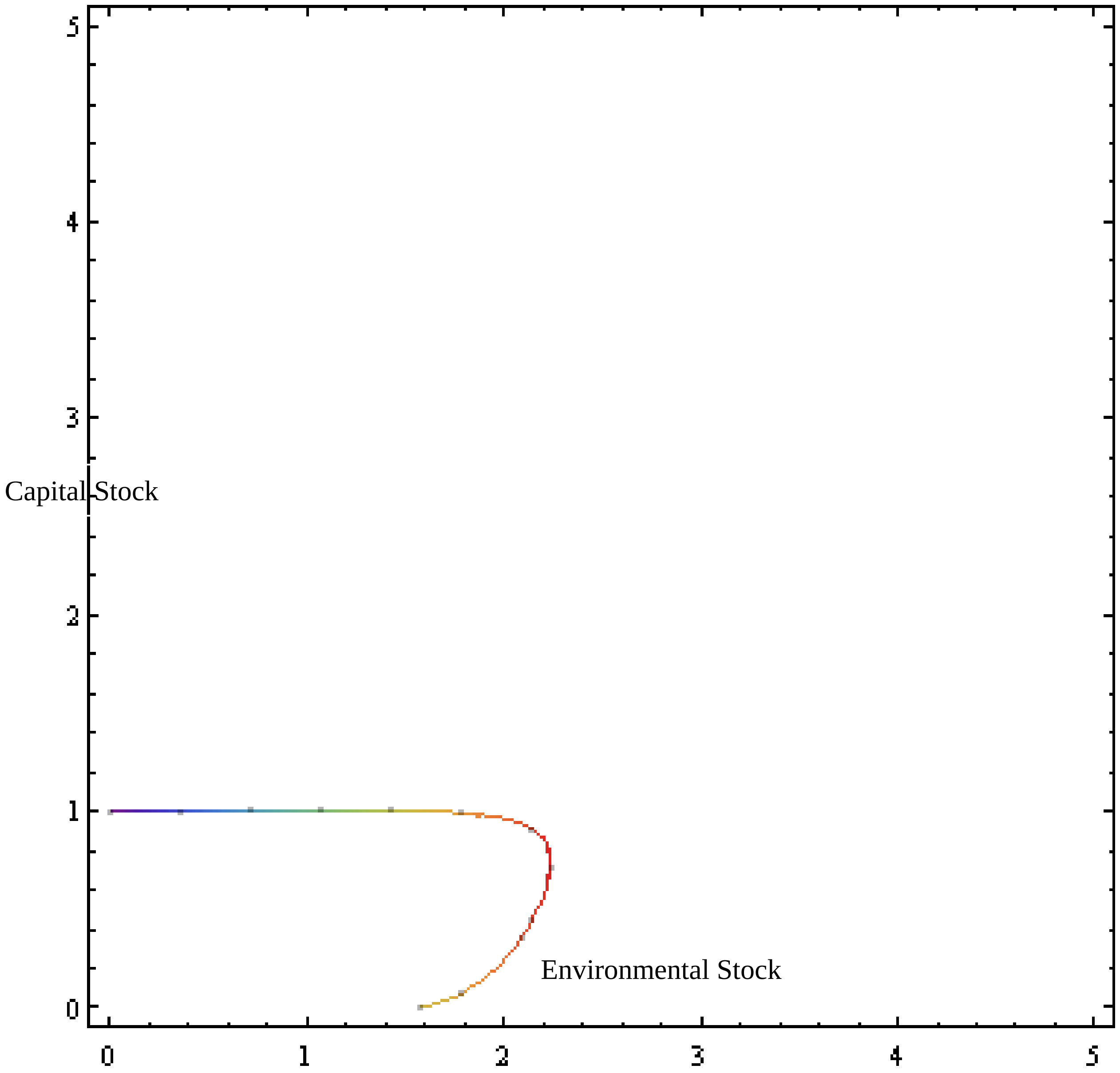

Figure 9: Steady State Relation between Capital and Environmental Stock for $\alpha=1$ and $\theta=.16$;

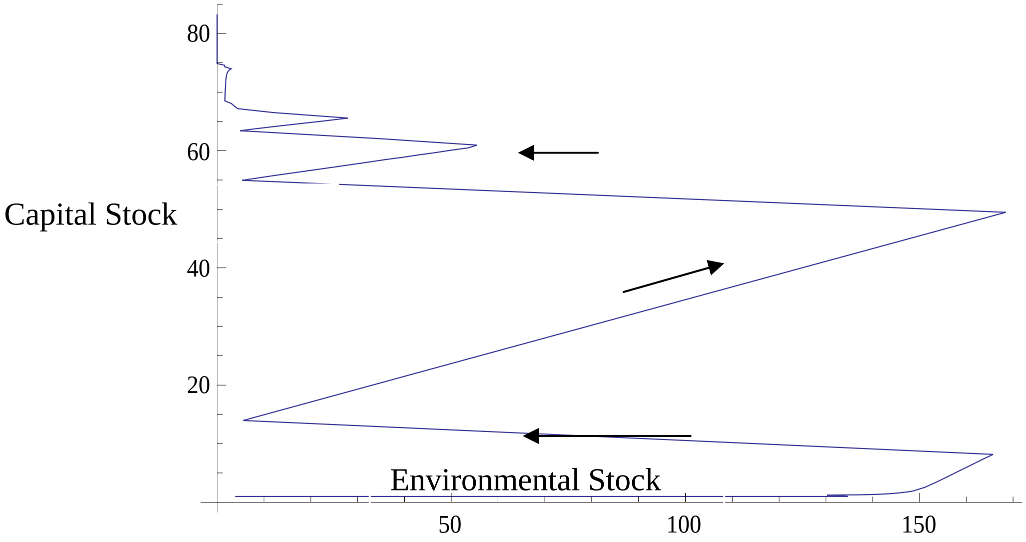

Figure 10: Time Path of Capital and Environment for $q_0 = 4, k_0 = 1, \alpha = 1, \beta = .03, \theta = .16$

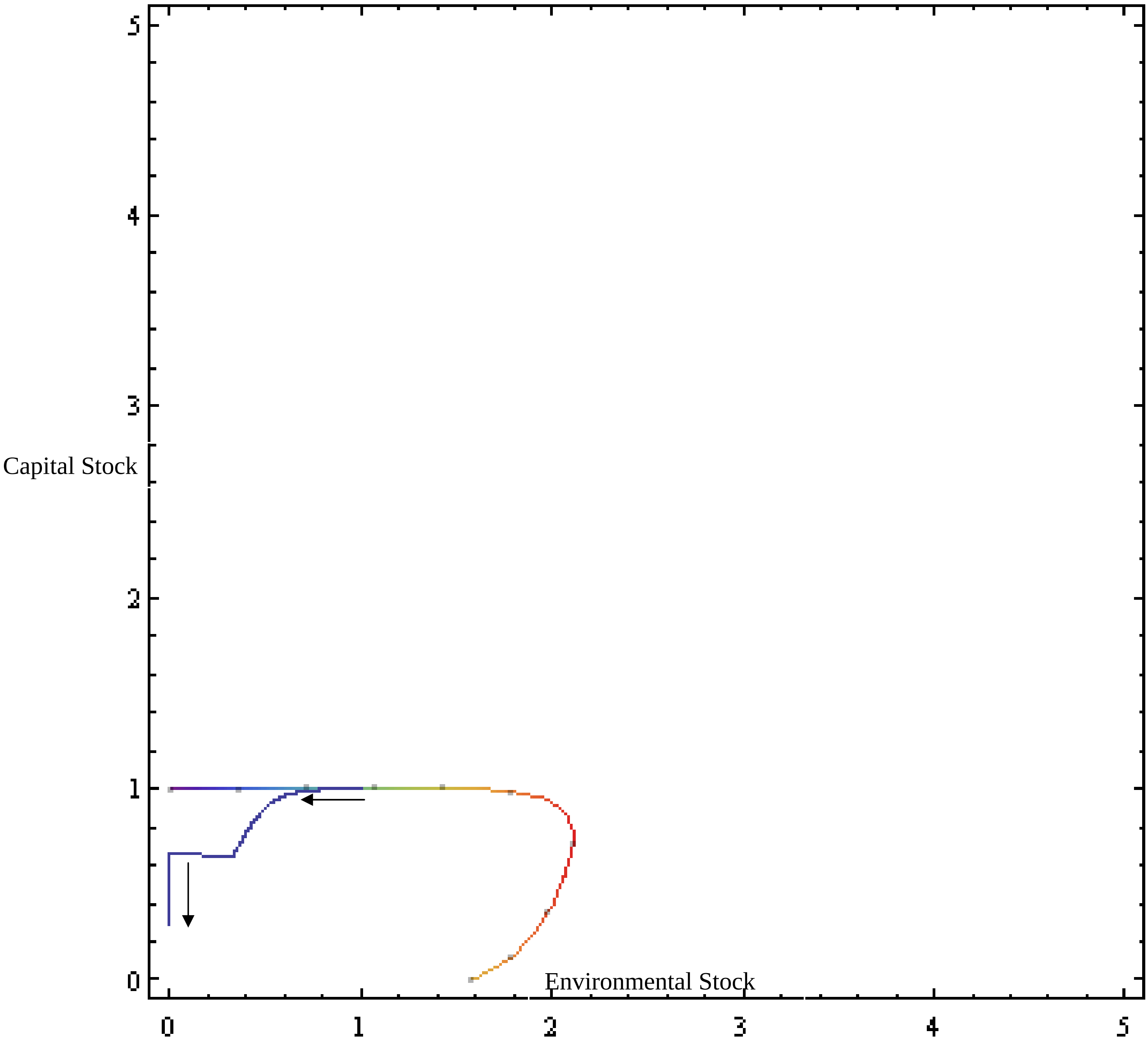

Figure 11: Time Path of Capital and Environment for $q_0 = 1, k_0 = 1, \alpha = 1, \beta = .03, \theta = .16$

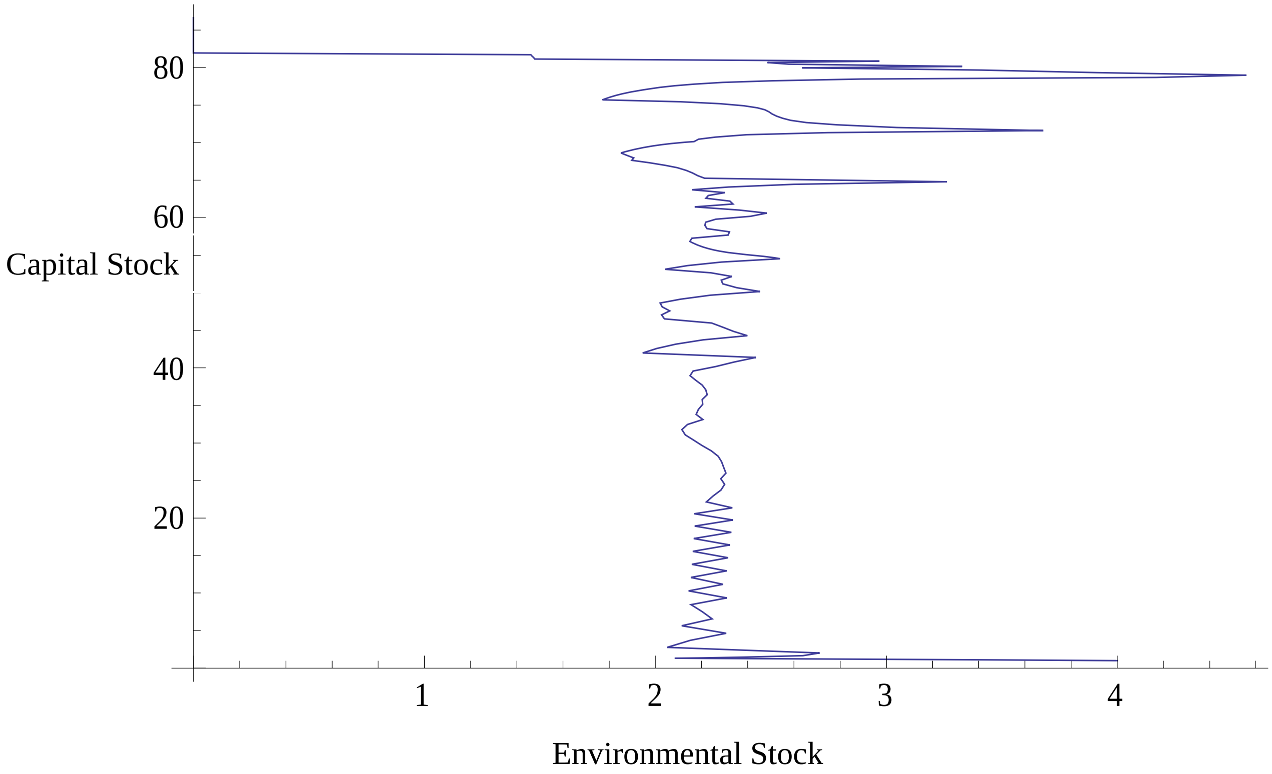

Figure 12: Time Path of Capital and Environment for the case of Risk from Natural Hazards

Note: $q_0 = 4, k_0 = 1, \alpha = 1, \beta = .03, \theta = .16, \lambda_0 = .001, \dot{\lambda} = .1\log(2.71828 + t)$