Environmental Resources Depletion and Interplay Between Negative and Positive Externalities in a Growth Model

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Summary

We analyse growth dynamics in an economy where the well-being of economic agents depends on three goods: leisure, a free access environmental good and a private good which can be produced by each agent through his own labour input. The private good can be consumed as a substitute for the environmental resource. The production process of the private good by each agent generates negative externalities on the other agents, by depleting the free access natural resource; but it also produces positive externalities by increasing the productivity of labour via a learning-by-doing mechanism of accumulation of knowledge [which is a pure public good]. In this context, we show that attracting steady states may exist which are Pareto-dominated by others where aggregate private consumption and labour productivity are lower. However, negative externalities can also be an engine of desirable growth: the deterioration of the environmental good can play the role of a coordination device leading economic agents to a wider exploitation of positive externalities.

Keywords: Self-protection choices, Consumption patterns, Negative externalities, Undesirable economic growth, Adaptive dynamics

JEL Classification: D62, O11, O13, O40, Q20

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INTRODUCTION

We present a model in which the deterioration of a free access environmental good is an engine of economic growth. In particular, we analyse the dynamics of an economy where only one private good is produced, which may be consumed as a substitute for a free access renewable environmental good or to satisfy needs different from those satisfied by the environmental resource[1]. The production process of the private good deteriorates the environmental resource and the deterioration of it [ceteris paribus] leads agents to increase their labour input in the production process of the private good in order to produce and consume higher quantities of the private good as a substitute for the environmental good. Clearly, this substitution mechanism may generate a self-enforcing economic growth process driven by the continuous increase of agents' needs for private consumption generated by the progressive reduction of the free consumption of the environmental good.

We study such mechanism in an adaptive model where the growth process is conditioned by both negative and positive externalities; agents take as exogenously given the aggregate negative impact of economic activity on the environmental good; so, the production of the private good by each agent generate negative externalities. However, the production process of the private good [which is assumed as non storable] by each agent generates positive externalities via a learning-by-doing mechanism of accumulation of knowledge [which is a pure public good].

In this context, negative externalities –through the substitution process described above- may lead agents towards a better exploitation of positive externalities driving the economy outside a poverty trap. However, we also show that there may exist growth paths along which the [cumulative] effect of positive externalities is not able to counterbalance that of negative externalities; that is, the economy may approach a fixed point characterized by relatively high consumption of private goods and accumulation of knowledge, which is Pareto-dominated by other fixed points with lower private consumption and accumulation of knowledge. In such case, economic growth is undesirable and is the consequence of a coordination failure.

The paper is organized as follows. Sections 1 and 2 deal with related literature; in sections 3, 4 and 5 we present the model; in sections 6, 7 and 8 we analyse it. Finally, Section 9 concludes the paper.

[1] Two goods are said [Edgeworth] substitutes if the marginal utility of one decreases as the quantity of the other increases [see e.g. Zhang (1999)].

1. RELATED LITERATURE

The “push factor” role played by the scarcity of natural resources has been pointed out by several empirical studies[2]. Rauch (1989) proves that the growth in pro-capita consumption has been slower in countries with relatively large endowment of land per capita. Sachs and Warner (1995) analyse a sample of 97 developing countries and consider the annual growth rates between 1970-89 and the exports of natural resources in 1970 of each country [resource-based exports are defined as agriculture, minerals, and fuels] and find that natural resource abundance and economic growth are inversely correlated over this period. For further references about empirical results see Sachs and Warner (1999)[3].

Said empirical results may be generated by certain mechanisms highlighted by economic literature. The idea that the scarcity of natural resources can play a part as “push factor” in economic growth processes was already contemplated in Karl Marx’s Capital [Capital, vol. I, ch.24 (sec.2)], as he credits a driving role to the Commons’ “enclosure” process in relation to the English Industrial Revolution. Marx seems to acknowledge a “push factor” role not only in relation to the agricultural productivity growth associated with enclosures, but also to the fact that a significant number of individuals excluded from access to the Commons contributed to the supply of “cheap labour” necessary for the take-off of the manufacturing industry[4]. The impact of the enclosures process in the creation of labour supply for the English manufacturing industry has been recently underlined by Humphries (1990):

“……..parliamentary enclosure eroded nonwage sources of subsistence available to semi-proletarian families and left them increasingly dependent on wages.……..As in many parts of the Third World today, semi-proletarianization took the form of the husband/father working for wages while the wife/mother and the children added to family subsistence by exploiting traditional rights to rural resources……..enclosure increased families’ dependence on wages and wage earners, pressures which can be understood only in the context of the importance of family participation in securing an eighteenth-century livelihood. If proletarianization is seen

[2] “The oddity of resource-poor economies outperforming resource-rich economies has been a constant motif of economic history. In the seventeenth century, resource-poor Netherlands eclipsed Spain, despite the overflow of gold and silver from the Spanish colonies in the New World. In the nineteenth and twentieth centuries, resource-poor countries such as Switzerland and Japan surged ahead of resource-abundant economies such as Russia. In the past thirty years, the world’s star performers have been the resource-poor Newly Industrializing Economies of East Asia- Korea, Taiwan, Hong Kong, Singapore- while many resource-rich economies such as the oil-rich countries of Mexico, Nigeria, Venezuela, have gone bankrupt.” [Sachs and Warner (1995), p.2]

[3] See Sachs and Warner (2001) for an interesting discussion about the robustness of the empirical evidence supporting the *curse of natural resources hypothesis*.

[4] Cohen and Weitzman (1975) elaborate a mathematical model, which provides a useful framework for the analysis of the role played by the enclosure movement as a push factor in English Industrial Revolution.

as a process of gradual elimination of sources of family subsistence other than wages, a causal link between the loss of common rights and wage dependence is reestablished.” (pp. 18-19)

Many recent works have focused on exposing several mechanisms through which the scarcity of resources may stimulate growth processes; some of the most interesting are those of Rauch (1989), Matsuyama (1992), Sachs and Warner (1995, 1999, 2001), Rodriguez and Sachs (1999), Auty (2001), Gylfason (2001). A review of the various studies on this matter is not contemplated by the present article [for a brief review, please refer to Auty (2001), Gylfason (2001), Sachs and Warner (2001)]; however, to sum them up, the most important explanations can be classified as follows:

1) Some authors have concentrated on exposing the channels by means of which the abundance of resources can affect the motivation and the efficiency of public administrators in implementing virtuous behaviours that are typically growth-inducing; that is to say, that characterize a “developmental state” [see e.g., Auty (1997, 2001), Gelb (1998)].
Within this context, the ways in which natural resource abundance may inhibit the growth process are various. Above all, a crucial role is played by the fact that in a resource-rich economy, public administrators are mainly encouraged to adopt rent-seeking behaviours, as opposed to enforcing growth-inducing activities [see e.g. Tornell and Lane (1994), Lane and Tornell (1996) Karl (1997), Desai (1998)].

2) Another possible explanation is provided by Rodriguez and Sachs (1999). They analyse a Ramsey-model according to which they theorize that, in each instant of time, a constant [yet declining in per capita terms] and exogenously given amount of natural resources is sold on international markets and the natural resource revenues are invested in domestic capital[5]. If the amount of natural resources exported in each instant of time is adequately large, the dynamics of the economy is characterized by an over-shooting effect: per capita capital accumulation and per capita consumption reach levels superior to those corresponding to the economy’s steady state. However, such levels cannot be sustained [as the pro capita revenues of natural resources diminish with time] and the level of capital converges to the steady state “from the right”, that is to say, revealing negative growth rates.

[5] However, the model’s results are still valid even under the assumption that the export of natural resources can be used also to import consumer goods, as well as to increment the productive capital.

The overshooting trend in the Rodriguez and Sachs model can also occur assuming that the export of natural resources is optimally determined. Within this context, overshooting phenomena may occur even in economies with a stable population[6].

3) We can provide a brief overview of the third mechanism, by means of which high availability of natural resources may inhibit economic growth, using the words of Sachs and Warner (2001):

"Most current explanations for the curse [*of natural resources*] have a crowding-out logic. Natural resources crowd-out activity *x*. Activity *x* drives growth. Therefore, natural resources harm growth. Since there is a diversity of views regarding the second of these statements [what exactly drives growth], we have a similar diversity of views on the natural resource question." [p. 833 (cursive added)][7]

Sachs and Warner (1995, 1999) identify *x* with traded-manufacturing activities and the crowding-out mechanism is the following: an increase of natural resources endowment may create an increase of demand for non-traded products driving up their prices. If these non-traded goods are inputs in the production process of traded-goods [e.g. labour], the increase of non-traded goods' prices reduces profits in the traded good sector [which sell its products on international markets at relatively fixed prices]. The consequent decline of the traded activities inhibits economic growth.

In Gylfason, Herbertsson and Zoega (1999) e in Gylfason (2001), the crowded-out sector *x* is *education*:

"…….nations that are confident that their natural resources are their most important asset may inadvertently –and perhaps even deliberately!- neglect the development of their human resources, by devoting inadequate attention and expenditure to education. Their natural wealth may blind them to the need for educating their children." [Gylfason (2001), p. 850]

Matsuyama (1992) identifies *x* with the industrial sector; in particular, he analyses an economy defined by two sectors – the agricultural sector and the industrial sector – in which

6 The only assumption that plays a key role in the Rodriguez and Sachs model is the lack of access to international asset markets where the economy could invest its natural resource revenues in international assets paying permanent annuities.
7 Obviously, we can include the explanations given under point 1) within this case. Even so, we preferred to keep them separate for the sake of clarity.

the scarcity of natural resources is represented by low productivity in the agricultural sector. Economic agents react to the low productivity of the agricultural sector by increasing labour input within the industrial sector, where an accumulation process of knowledge driven by a learning-by-doing mechanism works. Matsuyama's model is based on the open economy assumption, that is to say, economic agents may import goods not produced by the domestic agricultural sector. Positive externalities within the industrial sector and the possibility of substituting domestic agricultural products with imported ones are both essential elements of this model.

Within this context, Matsuyama shows that the economy's growth rate is inversely correlated to the productivity of the agricultural sector; he also demonstrates that low productivity of the agricultural sector can induce an economic growth path, which Pareto-dominates that of another economy with [ceteris paribus] a higher productivity of the agricultural sector.

Economic growth is always desirable in Matsuyama's model and in the other models in the abovementioned literature; that is, the increase of the activity level of sector x always leads to an increase of economic agents' well-being. In our model, we focus our attention on the analysis of the role that negative externalities -generated by the development of sector x- may play in determining growth dynamics and economic agents' well-being. Our main objective is to point out a mechanism according to which negative externalities may be an engine of economic growth and to show that economic growth may be associated with a reduction in economic agents' well-being, differently from the cases in which economic growth is fuelled exclusively by positive externalities.

2. SUBSTITUTES FOR NATURAL RESOURCES

The basic assumption on which our model is grounded concerns the existence of a private good, which can be consumed as a substitute for the free access environmental resource; in order to face the deterioration of the natural resource, economic agents may substitute consumption patterns and economic activities requiring high availability of the environmental resource with consumption patterns and economic activities less affected by environmental deterioration. Within this context, the increase in their labour input in sector x may be interpreted as a self–protection choice, enabling them to alleviate the negative consequences generated by the scarcity of natural resources.

The possibility of substituting natural resources with an increase of the activity level in sector x has essentially been contemplated in many of the abovementioned works. For example, we can consider Matsuyama's model; in this model, the possibility of substitution is made certain by foreign trade, which – through the export of the goods produced in sector x and the import of agricultural goods – allows a reduction of the damages generated by the low productivity of the domestic agricultural sector.

Substitution possibilities are various and those concerning the agricultural sector constitute only a portion of them. For example, let's consider the tourism sector; an economy can derive consistent revenues from such sector, which, ceteris paribus, possesses greater growth potential, the higher the endowment of environmental resources is. However, the revenues derived from the tourism sector can be substituted by the revenues produced by any other economic activity.

Other substitution possibilities are associated with the consumption of environmental resources as final goods rather than as intermediate goods. In this case, the scarcity of environmental resources can make "environment intensive" consumption patterns comparatively less attractive than those based on the consumption of private goods, which are less likely to experience the negative effects deriving from environmental deterioration.

The main focus of our model will concern the transformation of consumption patterns generated by environmental deterioration[8]. The notion that environmental deterioration may alter consumption patterns causing them to become more dependent on the consumption of private goods rather than on the consumption of free access environmental resources is shared by several works on the subject of environmental defensive expenditures [see e.g. Hueting (1980), Shibata and Winrich (1983), Leipert (1989), Shogren and Crocker (1993), Antoci (1996), Antoci and Bartolini (1999, 2004), Bartolini e Bonatti (2002)].

Here are some traditional examples. Mineral water may substitute spring water or tap water. Medicines may mitigate the effects of respiratory diseases caused by air pollution. Individuals may react to the deterioration of the seaside near home by going to a less deteriorated seaside area by car or by boat, they may build a swimming pool in their gardens, they may purchase houses in exclusive areas at the seaside or buy holiday-packages in tropical paradises. Individuals may defend themselves from external sources of noise by installing sound-proofing devices, and so on. However, the general insight provided by said literature is that individual reactions to environmental deterioration can be diverse and are

[8] However, this model can be easily modified in a two-sector model – the sector x and the agricultural or tourism sector – in which the natural resources enter as intermediate goods.

likely to deeply influence consumption patterns, increasing the consumption of private and expensive goods as opposed to free access environmental resources. Urban life offers an illustrative example of said substitution mechanism. Cities are often characterized by the scarcity of free access environmental resources and, at the same time, they are able to supply a considerable variety of private and expensive consumption opportunities [see e.g. Hueting (1980), Antoci and Bartolini (1999, 2004), Bartolini e Bonatti (2002)]. The scarcity of areas where individuals can meet away from the dangers of city traffic brings on additional expenses for childcare [baby-sitters, playgrounds, etc.], as well as for the leisure of adults. To a degree, the reason for the constant increase in the consumption of "home entertainment" in the industrial society can indeed be found in the substitution mechanism as previously defined[9].

In our model, individual substitutive consumption made with the aim of facing environmental deterioration generates negative externalities on all the other agents, as it furthers environmental deterioration. This context has been examined by Shogren and Croker (1991), who demonstrate that if the self-protecting choices of an economic agent "transfer" the environmental damage on to other economic agents, and if the economic agents do not coordinate themselves, then the self-protecting choices are enforced beyond the socially optimal level[10]. However, Shogren and Croker analyse a static model and do not develop their model in order to further examine the consequences that an "excess" of self-protecting choices may determine on economic growth, should the self-protecting choices involve the consumption of private goods and services. In our model we expand Shogren and Croker's work in this direction.

Beltratti (1996) analyses a model wherein environmental goods and private goods are substitute. Such model differs from ours for two main reasons. The first one relates to the fact that in Beltratti's model decisions are made by a social planner; therefore, there are no positive nor negative externalities, and consequently, such model is not likely to examine the cumulative effect determined by the interaction between positive and negative externalities, as we do in our model. The second reason is that Beltratti analyses a model in which the produced goods may be accumulated in order to become capital and in which labour input is exogenously given. In this context, an increase in the substituted consumption in the instant of

[9] A phenomenon that is in many instances considered a consequence of environmental deterioration and is often associated with a radical transformation of consumption patterns is rural exodus. With urbanization, consumption patterns tend to become market-oriented. The resources that were freely accessible in rural communities become accessible only through purchase on the market of substituted goods and, therefore, through entry in the labour market [see e.g. Humphries (1990), Myers (1997), Epstein and Jezeph (2001)].

[10] The distinction between self-protecting options that "transfer" negative externalities on to other economic agents and options that instead "filter" them has been introduced by Bird (1987).

time of reference cannot be achieved increasing the labour input, and therefore it completely weighs on the accumulation of capital, which is reduced; as a consequence, environmental deterioration inhibits growth in Beltratti's model[11].

The idea that environmental negative externalities can be an engine of economic growth was first introduced, in a mathematical model, by Antoci (1996) and Antoci and Bartolini (1997, 1999)[12]. In these works, the selection process of labour inputs and of consumption patterns is analysed in an evolutionary game context without accumulation of assets. Antoci and Bartolini (1994) contains a further development of such models.

Bartolini e Bonatti (2003) have analysed the dynamics of the accumulation of physical capital in an economy where agents possess perfect foresight and they have showed that it is possible to have undesirable economic growth generated by negative externalities even assuming that the economic agents are perfectly rational[13].

The present article intends to advance this pattern of research, analysing the dynamics of growth generated by the choices of economic agents, which "adapt" to the variations of the context in which they operate, variations that are caused both by negative [environmental deterioration] and by positive externalities [increase in labour productivity]. Within this framework, it is possible to point out some of the interaction mechanisms between positive and negative externalities that are likely to generate significant consequences in the growth process of an economy and in the well-being of economic agents[14].

3. THE MODEL

We analyze the dynamics of an economy with an infinite number [a continuum] of identical agents. In each instant of time *t*, the representative agent's well-being depends on three goods:

(1) Leisure: $1-l(t)$.

[11] It is correct to emphasize the fact that Beltratti's model focuses on proving that in the event of substituted consumption, the optimal co-evolution* of capital and environmental deterioration may not give rise to the environmental Kuznets' curve.

[12] The idea that negative externalities deriving from economic growth may, in their turn, "fuel" the growth process through the enforcement of defensive consumption has been contemplated by economic literature at least since Hirsh's famous work (1976). However, it was only recently that this idea was introduced in mathematical models.

[13] Antoci, Sacco e Vanin (2004) analyse a model wherein economic agents possess perfect foresight and accumulate physical and social capital; in such model, economic agents may face the negative externalities generated by a low level of social capital, by increasing their consumption of private goods. Within this context, the authors point out some of the mechanisms through which the accumulation of physical capital and the accumulation of social capital may end up being in conflict.

[14] Bartolini e Bonatti (2002) analyse a model in which growth is driven by environmental negative externalities and in which an asset is accumulated by way of a mechanism similar to the one considered in our model. However, Bartolini e Bonatti analyse the choices of the economic agents in a time span made up of a fixed number of periods. Then again such context (which is essentially a static optimization one) does not allow for the examination of the variety and stability of fixed points; consequently, it does not consent the comparative evaluation of well-being among alternative fixed points.

(2) A free access flow of a renewable environmental good: *E*(*t*).

(3) A flow of a non-storable private good produced by the agent: *Y*(*t*).

The flow *Y*(*t*) can be consumed by the representative agent as a substitute for the environmental good, $c_2(t)$, or to satisfy needs different from those satisfied by the environmental good, $c_1(t)$. Since *Y*(*t*) is not storable, it holds $Y(t) = c_1(t) + c_2(t)$.

The representative agent's production function

We assume that, in each instant of time *t*, the representative agent can produce the private good by the following production function

$$Y(t) = l(t)[K(t)]^{\alpha}$$

where *l*(*t*) represents the representative agent's labor input and *K*(*t*) represents knowledge capital; α is a parameter satisfying $0 < \alpha < 1$. As in Matsuyama (1992), we assume that *K*(*t*) is a pure public good. The environmental good is not an input in the production process of the private good.

The representative agent's utility function

We assume that *E* enters as a final good in the utility function of agents and that *E* and c_2 are perfect substitutes with marginal rate of substitution equal to the parameter *b*[15]; in particular, we assume that the representative agent's [instantaneous] utility function is the following

$$U(c_1, l, E + bc_2) = \ln(c_1) + a\ln(E + bc_2) + d\ln(1 - l) \quad (1)$$

with $a, b, d > 0$.

As an alternative, we could assume *E* to be an intermediate good, entering as input in some production function, for example, with regard to the tourism or agricultural sector. However, at least *a priori*, we do not expect such variation of the model to provide substantially diverging predictions, opposed to those regarding the model currently under analysis and therefore, for the sake of simplicity, we will only take into account the hypothesis in which *E* is a final good.

[15] The hypothesis of perfect substitutability between *E*(*t*) and $c_2(t)$ is made essentially for the sake of analytical simplicity; it could be relaxed by assuming that they are imperfect substitutes obtaining similar results.

Time evolution of *K*(*t*) and *E*(*t*)

We assume that knowledge capital *K*(*t*) evolves according to a learning-by-doing mechanism; in particular, the dynamics of $K(t)$ is given by the differential equation

$$\dot{K}(t) = \bar{l}(t)\left[K(t)\right]^{\alpha} - \eta K(t) \tag{2}$$

where $\dot{K}(t)$ is the time derivative of *K*(*t*), the parameter $\eta > 0$ is the depreciation rate of *K*(*t*), $\bar{l}(t)$ is the average labor input in the economy and consequently $\bar{l}(t)\left[K(t)\right]^{\alpha}$ represents the average production of private goods.

We assume that the dynamics of *E*(*t*) is given by

$$\dot{E}(t) = E(t)\left[\beta\left[\overline{E} - E(t)\right] - \gamma\bar{l}(t)\left[K(t)\right]^{\alpha}\right] \tag{3}$$

where $\beta E(t)\left[\overline{E} - E(t)\right]$ is the usual [logistic] regeneration function; the parameter $\beta > 0$ represents the regeneration rate of *E*(*t*) and the parameter $\overline{E} > 0$ represents the value that *E*(*t*) should approach if there were no production of private goods in the economy. So $\overline{E}$ may be interpreted as the "endowment" of the environmental good.

The rate of growth of *E*(*t*), $\dot{E}(t)/E(t)$, is negatively affected by the average production $\bar{l}(t)\left[K(t)\right]^{\alpha}$; the parameter $\gamma > 0$ measures the negative impact of average production on the growth rate of *E*(*t*).

4. THE CHOICES OF THE REPRESENTATIVE AGENT

Since in the economy there is a continuum of identical agents, the labor input choice *l*(*t*) of each of them doesn't modify the average value $\bar{l}(t)$. So, in each instant of time, the representative agent takes $\bar{l}(t)$ as exogenously given. This implies that he does not take into account the "shadow" prices of *E* and *K*; that is, in every instant of time, he is maximizing the utility function (1) with respect to the choice variables: l, c_1 and c_2.

In each instant of time t, the choices of the representative agent are defined by the following first order conditions

$$\frac{\partial U}{\partial l} = \frac{K^{\alpha}}{lK^{\alpha} - c_2} - \frac{d}{1-l} = 0 \quad (4)$$

[16]

$$\frac{\partial U}{\partial c_2} = -\frac{1}{lK^{\alpha} - c_2} + \frac{ab}{E + bc_2} \leq 0, \qquad c_2 \geq 0, \qquad c_2 \frac{\partial U}{\partial c_2} = 0 \quad (5)$$

From (4) and (5) we obtain the following choice functions

$$c_2 = \tilde{c}_2(K,E) \equiv 0 \qquad \text{if} \qquad E \geq \frac{ab}{1+d} K^{\alpha}$$

$$c_2 = \tilde{c}_2(K,E) \equiv \frac{1}{b(1+a+d)} \left[abK^{\alpha} - (1+d)E\right] \qquad \text{if} \qquad E < \frac{ab}{1+d} K^{\alpha}$$

$$l = \tilde{l}(K,E) \equiv \frac{1}{1+d} \qquad \text{if} \qquad E \geq \frac{ab}{1+d} K^{\alpha}$$

$$l = \tilde{l}(K,E) \equiv \frac{1}{b(1+a+d)} \left[b(1+a) - d\frac{E}{K^{\alpha}}\right] \qquad \text{if} \qquad E < \frac{ab}{1+d} K^{\alpha}$$

The choice of c_1 is obtained by subtracting the substitutive consumption $\tilde{c}_2$ from the output $\tilde{l}(K,E)K^{\alpha}$.

Note that the curve Ω, defined by the equation

$$E = \frac{ab}{1+d} K^{\alpha}$$

separates the positive orthant of the plane (K, E) in two regions; in the region above it, the environmental good is not perceived as "scarce" relatively to the value of K and the

[16] With the utility function (1), the conditions $0 < l(t) < 1$ and $c_1(t) > 0$ always hold.

representative agent has no incentive to produce and consume output as a substitute for the environmental good [that is, $\tilde{c}_2 = 0$]. Below Ω, the representative agent chooses $\tilde{c}_2 > 0$. Note that the labor input $\tilde{l}(K,E)$ is constant above Ω while it becomes a strictly decreasing function of *E* below Ω; if *E* decreases, given *K*, the representative agent has to work more to produce the private substitute for the environmental good.

5. GROWTH DYNAMICS

Since all agents are identical, the average labor input $\bar{l}$ coincides [ex-post] with the representative agent's choice $\tilde{l}(K,E)$. So, the dynamical system (2)-(3) becomes

$$\dot{K} = \tilde{l}(K,E)K^{\alpha} - \eta K$$
$$\dot{E} = E\left[\beta\left[\bar{E} - E\right] - \gamma\tilde{l}(K,E)K^{\alpha}\right] \tag{6}$$

The former equation of system (6) can be explicitly written as

$$\dot{K} = \frac{1}{1+d}K^{\alpha} - \eta K \tag{7}$$

for $\quad E \geq \frac{ab}{1+d}K^{\alpha}$ [that is, above the curve Ω], and

$$\dot{K} = \frac{1+a}{1+a+d}K^{\alpha} - \frac{d}{b(1+a+d)}E - \eta K \tag{8}$$

for $\quad E < \frac{ab}{1+d}K^{\alpha}$ [below the curve Ω].

The latter equation of system (6) can be explicitly written as

$$\dot{E} = E\left[\beta(\overline{E} - E) - \frac{\gamma}{1+d}K^{\alpha}\right] \tag{9}$$

for $E \geq \frac{ab}{1+d}K^{\alpha}$, and

$$\dot{E} = \frac{E}{b(1+a+d)}\left\{\beta b\overline{E}(1+a+d) - \gamma b(1+a)K^{\alpha} + \left[\gamma d - \beta b(1+a+d)\right]E\right\} \tag{10}$$

for $E < \frac{ab}{1+d}K^{\alpha}$.

Systems (7)-(9) and (8)-(10) describe dynamics above the curve Ω and below the curve Ω, respectively.

It is easy to check that $\dot{K}$ and $\dot{E}$ are continuous functions of *K* and *E* for every *K* and *E*[17]; furthermore, they are differentiable for every *K* and *E* such that $E \neq \frac{ab}{1+d}K^{\alpha}$.

Note that $\dot{K}$ is a decreasing function of *E* [given *K*]. More precisely, above Ω, the evolution of *K* doesn't depend on *E* [see equation (7)]; below Ω, $\dot{K}$ is a strictly decreasing function of *E* [see equation (8)]. Therefore, the accumulation of *K* is fuelled by the depletion of the environmental good. A reduction of *E* increases agents' need of private substitutes for the environmental good and consequently their labor supply. The consequent increase of aggregate output has a positive effect on the accumulation of *K* [positive externalities] but causes a further depletion of the environmental good [negative externalities]. Therefore, system (6) describes a self-enforcing mechanism according to which negative externalities are an engine of economic growth. By such mechanism, environmental degradation is not only a consequence of economic growth, but it plays a key role as a push factor in the growth process.

6. CLASSIFICATION OF DYNAMICS

In this section we give a classification of dynamic regimes under our model. Mathematical details are left to appendixes 1, 2 and 3. In such classification, we omit to consider "non-

[17] More precisely, they are Lipschitz functions.

robust" cases; that is, those dynamic regimes which hold only for particular values of the parameters of the model[18].

In the classification there are some threshold values of the parameters $\overline{E}$ and γ; when such values are crossed, the dynamics of the economy pass from one dynamic regime to another one. Remember that the parameter $\overline{E}$ may be interpreted as the endowment of the environmental good while the parameter γ represents the negative impact of economic activity on the environment.

These thresholds values are the following

$$\overline{E}^{*} \equiv \frac{\gamma + ab\beta}{\beta\left[\eta^{\alpha}(1+d)\right]^{\frac{1}{1-\alpha}}} \qquad \overline{E}^{**} \equiv \frac{\gamma}{\beta}\left(\frac{1+a}{\eta^{\alpha}(1+a+d)}\right)^{\frac{1}{1-\alpha}}$$

$$\overline{E}^{T} \equiv \frac{1-\alpha}{d}\left(\frac{\alpha\beta\left(b(1+a)\right)^{\frac{1}{\alpha}}}{\eta\left(\beta b(1+a+d)-\gamma d\right)}\right)^{\frac{\alpha}{1-\alpha}}$$

$$\overline{\gamma}^{L} \equiv \frac{\beta b}{d}\left[1+a+d-\alpha(1+a)(1+d)\right] \qquad \overline{\gamma}^{U} \equiv \frac{\beta b}{d}(1-\alpha)(1+a+d)$$

It always holds $\overline{\gamma}^{L} < \overline{\gamma}^{U}$, while $\overline{E}^{*} < \overline{E}^{**}$ if and only if

$$\gamma > \overline{\gamma} \equiv \frac{\beta ab}{\left(\frac{(1+a)(1+b)}{1+a+d}\right)^{\frac{1}{1-\alpha}} - 1}$$

where $\overline{\gamma}^{L} < \overline{\gamma} < \overline{\gamma}^{U}$ always.

Let us now give a classification of robust dynamic regimes under system (6). In the following figures, attractive fixed points of dynamics are represented by full dots $(\bullet)$,

[18] More precisely, we define as "non-robust" the dynamic regimes that are observed only if an equality condition on the values of parameters is satisfied.

repulsive points by open dots (∘) and saddle points by drawing their stable and unstable manifolds[19] only.

Case: $\overline{\gamma}^{U} \leq \gamma$

This case is characterized by a relatively high value of γ. The corresponding dynamic regimes are showed in figures 1-3. There are three sub-cases; each of them is associated with an interval of values of the parameter $\overline{E}$. If $\overline{E} > \overline{E}^{**}$, then there exist four fixed points [see figure 1]: the repulsive fixed point O, the saddles C and F, and the [globally] attracting fixed point D. In D, it holds $E > \frac{ab}{1+d}K^{\alpha}$ [that is, D lies above the curve Ω]; therefore, in such a point, there is no scarcity of the environmental good [relatively to the value of *K*] and, consequently, agents don't consume output as a substitute for the environmental good.

If $\overline{E}^{*} < \overline{E} < \overline{E}^{**}$, then dynamics is characterized by a bi-stable regime in which there exist two [locally] attracting fixed points), C and D [see figure 2]. Almost all trajectories approach either C or D and their attraction basins are separated by the stable manifold Γ of the saddle point A. The fixed point O is repulsive and the fixed point F is a saddle. In the attracting fixed point C the environmental resource is completely depleted and agents have to rely completely on the consumption of the private good as a substitute for the environmental good.

If $\overline{E} < \overline{E}^{*}$, then the fixed point C is globally attracting, the fixed point O is repulsive and the fixed point F is a saddle [see figure 3].

Case: $\gamma \leq \overline{\gamma}^{L}$

This case is characterized by a relatively low impact of economic activity on environment. The corresponding dynamic regimes are showed in figures 4-6. All possible dynamics are characterized by the existence of a globally attracting fixed point. If $\overline{E} > \overline{E}^{*}$, in the [globally] attracting fixed point D agents don't consume substitutes for the environmental good [see figure 4]. If $\overline{E}^{**} < \overline{E} < \overline{E}^{*}$, in the attracting fixed point B it holds $E > 0$ but the relatively low level of *E* induces agents to consume a share of output as a substitute [see figure 5]. If $\overline{E} < \overline{E}^{**}$, in the attracting fixed point C the environmental good is completely depleted [see figure 6].

[19] The stable [unstable] manifold of a saddle type fixed point is the subset of the positive orthant of the plane (*K*, *E*) constituted by the union between the two trajectories approaching [respectively, diverging from] the fixed point and the fixed point itself.

Case: $\overline{\gamma}^{L} < \gamma < \overline{\gamma}^{U}$

Remember that, in this case, it holds $\overline{E}^{*} < \overline{E}^{**}$ if and only if $\gamma > \overline{\gamma}$ [where $\overline{\gamma}^{L} < \overline{\gamma} < \overline{\gamma}^{U}$ always]. Furthermore, it always holds $\overline{E}^{T} > \max\left(\overline{E}^{*}, \overline{E}^{**}\right)$ [see mathematical appendixes].

This case presents the highest number of possible dynamic regimes. However, there is only one regime, which is qualitatively different from those already encountered in figures 1-6, specifically, the one corresponding to the sub-case $\overline{E}^{T} > \overline{E} > \max\left(\overline{E}^{*}, \overline{E}^{**}\right)$ and represented in figure 7. In such regime, there exist six fixed points: A, B, C, D, F, O. The fixed points B and D are locally attractive; almost all trajectories approach either B or D and their attraction basins are separated by the stable manifold Γ of the saddle A. The remaining fixed points are repulsive or saddles.

In D agents don't consume output as a substitute for the environmental good while in B they do. In this case, as opposed to the bi-stable regime represented in figure 2, in the attractive fixed point below the curve Ω the environmental resource is not completely depleted.

The remaining dynamics can be classified as follows. If $\overline{E} > \overline{E}^{T}$, dynamics is [qualitatively] the same as the one depicted in figure 4; if $\overline{E}^{*} > \overline{E} > \overline{E}^{**}$ [$\gamma < \overline{\gamma}$], dynamics is the same as the one represented in figure 5; if $\overline{E}^{**} > \overline{E} > \overline{E}^{*}$ [$\gamma > \overline{\gamma}$], the corresponding dynamic regime is that showed in figure 2; finally, if $\overline{E} < \min\left(\overline{E}^{*}, \overline{E}^{**}\right)$, the dynamic regime is the same as that showed in figure 6.

7. INTERPRETATION OF RESULTS

In order to interpret the results of the classification defined above, it is useful to compare the dynamics we have described with that under the assumption *b* = 0. If *b* = 0, there is no possibility of substitution between the private good and the environmental good and the dynamics is described by system (7)-(9) only, which in such case holds for every *K* and *E*. Under the assumption *b* = 0, it holds $\dot{K} = 0$ for *K* = 0 and along the vertical line $K = \overline{K}_1 \equiv 1/\left[\eta(1+d)\right]^{\frac{1}{1-\alpha}}$ [see appendixes]. This means that environmental degradation doesn't affect the accumulation of *K*[20] and, consequently, dynamics becomes very simple. In particular, there always exists a globally attracting fixed point in which $K = \overline{K}_1$.

[20] This occurs as we are analysing an economy made up of a continuum of agents; as a consequence, the economic activity of each agent does not have a relevant impact on the environmental good and in the absence of

In the case $b > 0$, above the curve Ω, the locus $\dot{K} = 0$ coincides with the locus $\dot{K} = 0$ in the case b = 0; however, below the curve Ω, it lies entirely on the right of the line $K = \overline{K}_1$. This implies that the region where $\dot{K} > 0$ is wider in case $b > 0$ than in case b = 0 [see figures 1-7]. Therefore, the evolution of *K* is sensibly conditioned by the value of *E* and this gives rise to the variety of possible dynamic regimes showed in the previous classification.

Note that, in the case $b > 0$, the accumulation level $\overline{K}_1$ may still be reached by the economy; in particular, it is the value assumed by *K* at the fixed point D [when it exists], where private goods are not consumed as substitutes [see figures 1, 2, 4, 7]. However, for $b > 0$, $\overline{K}_1$ is the minimum accumulation level that the economy may reach starting from a strictly positive value of *K*. If the economy doesn't approach D, then it follows a trajectory converging to a fixed point with a higher value of *K*.

From the above classification, note that [ceteris paribus] D exists if and only if the endowment $\overline{E}$ is high enough, that is if $\overline{E} \in (\overline{E}^*, +\infty)$ [see the cases represented in figures 1, 2, 4 and 7], where $\overline{E}^*$ is a strictly increasing function of γ; when the value of γ increases, the threshold value $\overline{E}^*$ increases[21].

In the context $\overline{E} \in (\overline{E}^*, +\infty)$, D is globally attracting if $\overline{E}$ is high enough [see cases represented in figures 1 and 4]; otherwise, dynamics is characterized by a bi-stable regime [figures 2 and 7] where the economy approaches D only if it starts sufficiently near to it. Observe that, in the bi-stable regimes, the stable manifold Γ of the saddle A can be considered as the graph of a strictly increasing function $E = \tilde{\Gamma}(K)$ defined for every $K \in (0, +\infty)$[22]. Given any initial value $K^0 > 0$ of *K*, the economy reaches D if the initial value E^0 of *E* is such that $E^0 > \tilde{\Gamma}(K^0)$ while it approaches the other attracting fixed point [B in figure 7, C in figure 2] if $E^0 < \tilde{\Gamma}(K^0)$. Therefore, in bi-stable regimes, whatever the initial value $K^0 > 0$ of *K* is, the economy can always follow a development trajectory leading it to the fixed point B or C if the initial value E^0 of *E* is low enough. Being $E = \tilde{\Gamma}(K)$ a strictly

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coordination [for example, by means of a social planner], none of them will enforce activities for the protection of the environmental good.

21 Observe that $\overline{E}^*$ reaches a strictly positive minimum for $\gamma = 0$; consequently, if $\overline{E}$ is too low, then D doesn't exist whatever the value of γ is.

22 It is easy to check that the function $E = \tilde{\Gamma}(K)$ has not a vertical asymptote for *K* > 0; consequently, it is defined for every *K* > 0.

increasing function, the lower K^0 is, the lower E^0 must be for the economy to approach B or C.

In bi-stable regimes, from the point of view of knowledge capital *K*, the fixed point D is a "poverty trap" with respect to the fixed points B and C. However, as we shall see in the following section, agents' well-being at the fixed point D may be higher than that at the fixed points B and C.

If $\overline{E} \in (0, \overline{E}^*)$, the endowment of the environmental good is too low for the existence of the fixed point D; dynamics always reaches a globally attracting fixed point where *K* is greater than $\overline{K}_1$ and output is consumed as a substitute for the environmental good [see cases represented in figures 3, 5 and 6].

8. WELL-BEING ANALYSIS AND COMPARATIVE DYNAMICS

Note that all the fixed points with $K > 0$ are characterized by an inverse relation between *K* and *E*: the lower the value of *K* is at such points, the higher the value of *E* is. Since representative agent's labor supply $\tilde{l}(K, E)$ is increasing in *K* and decreasing in *E*, this means that going from the left to the right of plane (*K*, *E*) we encounter fixed points with higher levels of accumulation *K*, of work effort, of private consumption and of environmental degradation. Therefore, in an economy where agents do not internalize negative and positive externalities, it is possible that a correlation between the value of *K* [and of the aggregate output] and the agents' well-being will not exist. This paragraph aims at calculating the value assumed by the utility function of the representative agent in the different fixed points of the dynamic regime in relation to the variation of the most significant parameters of the model. Given that, in most cases, it is not possible to determine the coordinates of fixed points, it is necessary to resort to some numerical examples.

Numerical exercise 1 (figure 8)

The first example of numerical exercise we shall consider is the one showed in figure 8. In such figure, for sake of simplicity, only a portion of curves $\dot{K} = 0$ and $\dot{E} = 0$ has been traced, specifically that which lays under curve Ω. The corresponding dynamic regime is the one defined in figure 7 (to each fixed point is associated the value U that the utility function assumes in it). We can observe the existence of an inverse correlation between the value of *K* and well-being. The fixed point D [attracting], which has the lowest accumulation level, Pareto-dominates all the others; in particular, it dominates the other attracting fixed point, point B.

The fixed point A also dominates B, yet A is a saddle and therefore it is unstable.

Numerical exercise 2 (figure 9)

Figure 9 shows the values assumed by the utility function in each of the fixed points A, B, C, D of the bi-stable regime represented in figure 7 in relation to the variation of parameter *b* [the marginal rate of substitution between the private good and *E*]. It is worth remembering that in D the accumulation is at its lowest possible level; then A, B and C follow, in this order. We observe that the value of the utility function in D does not depend on the value of the parameter *b*, given that in D output is not consumed as a substitute for the environmental good. In the other fixed points, the utility increases as *b* increases. We notice that, as *b* increases, at first D dominates all the other fixed points; particularly, it dominates B, which is the other attracting fixed point of the bi-stable regime. Then, in case of considerably high values of *b*, B dominates D.

Numerical exercise 3 (figure 10)

This numerical exercise shows the variation of economic dynamics and of the value of the utility function in relation to the variation of parameter *b*; in figure 10 we can observe that, with $b = 0.4$, the point D is globally attracting [dynamics described in figure 4] and dominates the saddle C. With *b*=0.8, we experience the same dynamic regime; however, curves $\dot{K} = 0$ and $\dot{E} = 0$ are closer to each other and the difference between the values of the utility function in D and C is reduced. With *b*=1.2 we achieve a bi-stable regime [dynamics described in figure 7], in which D dominates all the other fixed points, in particular B, the other attracting fixed point. The point B is also dominated by A, which however is a saddle point. Finally, with *b*=1.6, the point D is very near to the point A and the point B is very close to the point C; if *b* further increases, the bi-stable regime ceases to exist and C becomes globally attracting [dynamics described in figure 6].

It is interesting to notice in this example that in cases with *b*=0.4 and *b*=0.8, the value of the utility function assumed in D [which is globally attracting] is higher than that of B in cases with *b*=1.2 and *b*=1.6. This suggests that an improvement in the substitution possibilities between the output and the environmental good does not always produce desirable effects. In fact, in this example, as *b* increases, the attracting fixed point B "emerges", dominated by D, which does not exist with lower values of *b*.

Numerical exercise 4 (figure 11)

In figure 11 we consider an example that can help to show how the dynamics of economy and of well-being can be influenced by variations of γ, the parameter measuring the impact on the environment due to economic activity. With $\gamma = 0.04$, D is globally attracting [dynamics described in figure 4]. The same applies with $\gamma = 0.07$; however, in this case, the curves $\dot{K} = 0$ and $\dot{E} = 0$ are closer to each other. With $\gamma = 0.1$ and $\gamma = 0.12$, said curves meet, producing the bi-stable regimes defined in figures 7 and 2 respectively. It is worth mentioning that an increase in γ gives rise to an attracting fixed point, possessing a level of accumulation higher than that of D. Therefore, an exogenous increase of γ can lead to an increase of K and of the aggregate output. We observe that in both cases of bi-stable dynamics, D dominates the other attracting fixed point [B in the case $\gamma = 0.1$, C in the case $\gamma = 0.12$].

Numerical exercise 5 (figure 12)

Figure 12 shows the effects produced by the variation of parameter $\overline{E}$, which measures the endowment of environmental good. With $\overline{E} = 2.8$, the point C is globally attracting [dynamics described in figure 6]. With $\overline{E} = 5.6$, the fixed points A and D emerge, very near to each other [dynamics described in figure 2], and D Pareto-dominates both A and C. As the endowment increases, for $\overline{E} = 8.4$, the point B also emerges and it becomes attracting in place of C [dynamic described in figure 7]. Finally, for $\overline{E} = 11.2$, the point D becomes globally attracting [dynamics described in figure 4]. In all the considered cases, the point D [when it exists] dominates all the other fixed points. Please note, in this example as well as in the preceding ones, how comparatively high the gap is between the value of K in D and the value of K in the fixed points dominated by D.

Numerical exercise 6 (figure 13)

Figure 13 considers the consequences associated with a variation of parameter β, measuring the regeneration rate of the environmental good. For $\beta = 0.04$, the points D and C are both attracting [dynamics described in figure 2]. With $\beta = 0.07$, the curves $\dot{K} = 0$ and $\dot{E} = 0$ come closer to each other, and with $\beta = 0.1$, they meet under Ω at the points A and B, with B being attracting [dynamics described in figure 7]. Finally, with $\beta = 0.12$, D becomes globally attracting. This exercise shows how a reduction in the regeneration capacity of the environmental good can produce an increase in the value of K and of the aggregate production. In fact, as β decreases, some attracting fixed points emerge, in which K assumes values higher than those in D. Even in this example, in the fixed points, well-being is inversely correlated to the value of K.

9. CONCLUSION

The general prediction of the model is that the higher the environmental impact γ and the substitution rate b are and the lower the endowment $\overline{E}$ of the environmental good and the regeneration rate β are, the higher the economy's accumulation and consumption level will be. An exogenous reduction of $\overline{E}$ and of β, or an exogenous increase of γ or of b may generate an increase of the aggregate product and of the level of K in the economy. Economic growth is fueled by the increase of "work motivation" of the economic agents, as a consequence of the gradual deterioration of the environmental resource, which induces agents to alter their consumption patterns, concentrating more and more on the consumption of private and expensive goods, rather than on the consumption of free access environmental goods.

This study has proved that, in the analysed economy, two different "undesirable" settings are possible, both a consequence of a coordination failure among economic agents; the economy may reach a "poverty trap", characterized by a low level of accumulation of knowledge capital – from which economic agents could step out by increasing their private consumption and their labour input within the industrial sector – or else, economy could converge to a "private consumption trap", characterized by an excessive consumption of private goods – from which economic agents could step by reducing their labour input.

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APPENDIX 1: BASIC MATHEMATICAL RESULTS FOR SYSTEM (7)-(9)

For simplicity, we will not consider "non-robust" dynamics; that is, those corresponding to equality conditions on parameter values. In the positive orthant of the plane (*K*, *E*), the dynamics of the economy is described by system (7)-(9) for $E \geq \frac{ab}{1+d} K^{\alpha}$, by system (8)-(10) in the complementary region. The curve

$$E = \frac{ab}{1+d} K^{\alpha} \tag{11}$$

separates the two regions.

Let us first analyze system (7)-(9). Under such system, it holds $\dot{K} = 0$ for $K = 0$ or

$$K = \overline{K}_1 \equiv \left(\frac{1}{\eta(1+d)} \right)^{\frac{1}{1-\alpha}} \tag{12}$$

and $\dot{E} = 0$ for $E = 0$ or along the curve

$$E = \overline{E} - \frac{\gamma}{\beta(1+d)} K^{\alpha} \tag{13}$$

We observe that (13) intersects (11) at a point in which it holds

$$K = \overline{K}_2 \equiv \left(\frac{\beta(1+d)\overline{E}}{\gamma + ab\beta} \right)^{\frac{1}{\alpha}} \tag{14}$$

Let us now look for fixed points under system (7)-(9). Notice that there exists always the fixed point $(K, E) = (0, \overline{E})$. Furthermore, there exists a fixed point with $K>0$ and $E > \frac{ab}{1+d} K^{\alpha}$ if and only if (iff) $\overline{K}_2 > \overline{K}_1$; that is, iff

$$\overline{E} > \overline{E}^{*} \equiv \frac{\gamma + ab\beta}{\beta\left[\eta^{\alpha}(1+d)\right]^{\frac{1}{1-\alpha}}} \tag{15}$$

Under system (7)-(9), it holds $\dot{E} > 0$ on the left of (13) and $\dot{E} < 0$ on the right. Furthermore, it holds $\dot{K} > 0$ on the left of the straight line (12) and $\dot{K} < 0$ on the right.

Since at the fixed points the loci $\dot{K} = 0$ and $\dot{E} = 0$ always intersect transversally, the fixed points are always hyperbolic[23]; this implies that they can be of three types only: sinks [attracting], sources [repelling] and saddles. So it is very easy to check that under system (7)-(9) the fixed point $(0, \overline{E})$ is a saddle and the fixed point with $K>0$, when existing, is a sink.

APPENDIX 2: BASIC MATHEMATICAL RESULTS FOR SYSTEM (8)-(10)

The loci where $\dot{K} = 0$ and $\dot{E} = 0$

Under system (8)-(10), it holds $\dot{K} = 0$ along the curve

$$E = \frac{b}{d} K\left[(1+a)K^{\alpha-1} - (1+a+d)\eta\right] \tag{16}$$

Note that the function (16) is strictly concave; it is initially an increasing function of K and subsequently it becomes decreasing. Furthermore, it holds $\dot{K} > 0$ below the curve (16) and $\dot{K} < 0$ above it.

Since $\dot{K}$ is a continuous decreasing function of E in the positive orthant of the plane (K, E), below the curve (11) it holds $\dot{K} > 0$ when $K \leq \overline{K}_1$ [see (12)]. This implies that, below (11), the locus $\dot{K} = 0$ lies entirely in the region with $K > \overline{K}_1$.

It holds $\dot{E} = 0$ for $E = 0$ and along the curve

$$E = \frac{b}{\gamma d - \beta b(1+a+d)}\left[\gamma(1+a)K^{\alpha} - \beta(1+a+d)\overline{E}\right] \tag{17}$$

if $\gamma d - \beta b(1+a+d) \neq 0$, or along the straight line

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[23] That is, they have eigenvalues with real part different from zero.

$$K = \left(\frac{\beta \overline{E}(1+a+d)}{\gamma(1+a)} \right)^{\frac{1}{\alpha}} \tag{18}$$

if $\gamma d - \beta b(1+a+d) = 0$. Note that, when $\gamma d - \beta b(1+a+d) > 0$, (17) is a strictly increasing function of K and it is strictly concave. The opposite holds if $\gamma d - \beta b(1+a+d) < 0$. Furthermore, in the plane (K, E), it holds $\dot{E} > 0$ on the left of (17), (18) and $\dot{E} < 0$ on the right.

Let us now look for the intersection points between the K-axis and the curves (16), (17). It is easy to check that (16) meets the K-axis at the point

$$K = \overline{K}_3 \equiv \left(\frac{1+a}{\eta(1+a+d)} \right)^{\frac{1}{1-\alpha}} \tag{19}$$

and (17) meets the K-axis at the point

$$K = \overline{K}_4 \equiv \left(\frac{\beta \overline{E}(1+a+d)}{\gamma(1+a)} \right)^{\frac{1}{\alpha}} \tag{20}$$

where $\overline{K}_4 > \overline{K}_3$ iff

$$\overline{E} > \overline{E}^{**} \equiv \frac{\gamma}{\beta} \left(\frac{1+a}{\eta^{\alpha}(1+a+d)} \right)^{\frac{1}{1-\alpha}} \tag{21}$$

The fixed points under system (8)-(10)

Let us now look for the fixed points under system (8)-(10), that is the fixed points lying below the curve (11). Observe that there always exists a fixed point $(K, E) = (\overline{K}_3, 0)$ where the environmental good is completely depleted. Let us now consider fixed points in which $E > 0$, corresponding to the intersections between (16) and (17)-(18). Note that the curves (16) and (18) have at most one intersection point; so, there exists at most one fixed point for $\gamma d - \beta b(1+a+d) = 0$. For $\gamma d - \beta b(1+a+d) \neq 0$, by plugging together the right hand sides of equations (16) and (17), we obtain the following equation

$$\beta b(1+a)K^{\alpha} = \beta d\overline{E} - \eta[\gamma d - \beta b(1+a+d)]K \qquad (22)$$

The solutions of (22) give the values of K at the fixed points with $E > 0$. Observe that the function of K on the left side of (22) is strictly concave, while the right side of (22) represents a straight line. Therefore, there exists at most one fixed point of system (8)-(10) with $E > 0$ if

$$\gamma d - \beta b(1+a+d) \geq 0 \;\; \text{[that is, } \gamma \geq \frac{\beta}{d} b(1+a+d)\text{]}$$

and there exist at most two fixed points if

$$\gamma d - \beta b(1+a+d) < 0 \;\; \text{[that is, } \gamma < \frac{\beta}{d} b(1+a+d)\text{]}$$

Some mathematical results about the case: $\gamma < \frac{\beta}{d} b(1+a+d)$

Let us define $f(K) \equiv \beta b(1+a)K^{\alpha}$ and $g(K) \equiv \beta d\overline{E} - \eta[\gamma d - \beta b(1+a+d)]K$ [see equation (22)]. As said above, $f(K)$ is a strictly concave function while $g(K)$ represents a straight line with positive slope which translates downward if the value of $\overline{E}$ goes down. Consequently, fixed all parameters' values except that of $\overline{E}$, there always exists a value of $\overline{E}$, $\overline{E}^T$, by which the graphs of $f(K)$ and $g(K)$ are tangent for some value of $K > 0$; let us indicate such a value by $\overline{K}^T$. If

$$\overline{K}_1 < \overline{K}^T < \overline{K}_3$$ [24]

then the point of tangency lies below the curve (11) in the plane (K, E) and at such point it holds $E > 0$. In such case, for $\overline{E}$ near enough to $\overline{E}^T$, $\overline{E} < \overline{E}^T$, there exist two fixed points with $E > 0$ lying below the curve (11) [see figure 14]. If $\overline{K}_1 > \overline{K}^T$ [see figure 15], then a reduction of $\overline{E}$ cannot generate two fixed points. The same holds if $\overline{K}_3 < \overline{K}^T$ [see figure 16].

Let us now see what are the conditions on parameters' values giving rise to cases $\overline{K}_1 < \overline{K}^T < \overline{K}_3$, $\overline{K}_1 > \overline{K}^T$ and $\overline{K}_3 < \overline{K}^T$. To this end, note that the value of $\overline{K}^T$ is obtained by solving the equation $f'(K) = g'(K)$, which gives the value

[24] See (12) and (19).

$$\overline{K}^T \equiv \left(\frac{\alpha\beta b(1+a)}{\eta\left[\beta b(1+a+d)-\gamma d\right]} \right)^{\frac{1}{1-\alpha}} \tag{23}$$

It is easy to check that $\overline{K}_1 < \overline{K}^T$ iff

$$\gamma > \overline{\gamma}^L \equiv \frac{\beta b}{d}\left[1+a+d-\alpha(1+a)(1+d)\right] \tag{24}$$

and $\overline{K}^T < \overline{K}_3$ iff

$$\gamma < \overline{\gamma}^U \equiv \frac{\beta b}{d}(1-\alpha)(1+a+d) \tag{25}$$

where $\overline{\gamma}^L < \overline{\gamma}^U < \frac{\beta b}{d}(1+a+d)$ always.

The value of $\overline{E}^T$ is easily determined by substituting $K = \overline{K}^T$ in equation (22) and solving it with respect to $\overline{E}$; after straightforward calculations, we obtain

$$\overline{E}^T \equiv \frac{1-\alpha}{d}\left(\frac{\alpha\beta\left(b(1+a)\right)^{\frac{1}{\alpha}}}{\eta\left(\beta b(1+a+d)-\gamma d\right)} \right)^{\frac{\alpha}{1-\alpha}} \tag{26}$$

APPENDIX 3: CLASSIFICATION OF DYNAMICS

We can now classify the dynamic regimes under our model.

Case I: $\gamma \geq \frac{\beta}{d} b(1+a+d)$

The curve $\dot{E} = 0$ is downward sloping [see (13)] above the curve (11) while it is strictly increasing or lies on a vertical straight line below it [see figures 1-3]. In such context, $\overline{K}_3 < \overline{K}_4$ implies $\overline{K}_1 < \overline{K}_2$[25]; therefore, it always holds $\overline{E}^* < \overline{E}^{**}$[26]. So, excluding non-robust

[25] Remember that $\overline{K}_1$ and $\overline{K}_3$ are the values of K in correspondence of which the curve $\dot{K} = 0$ intersects the curve (11) and the K-axis respectively; $\overline{K}_2$ and $\overline{K}_4$ are the values of K in correspondence of which the curve $\dot{E} = 0$ intersects the curve (11) and the K-axis respectively [see (12), (14), (19) and (20)].

cases, the possible dynamic regimes are those showed in figures 1-3 of the main text. Stability analysis can be worked out by simply analyzing the "arrow diagrams" in figures 1-3. In fact, in such cases, the loci $\dot{K} = 0$ and $\dot{E} = 0$ always intersect transversally. Therefore, the fixed points are always hyperbolic; this implies that they can be of three types only -saddles, sources [repelling] or sinks [attracting]- and consequently the classification of each fixed point is straightforward.

Case II: $\gamma < \frac{\beta}{d} b(1 + a + d)$

Sub-case II.1: $\bar{\gamma}^{U} \leq \gamma$ [27]

From figure 16 note that, as in case (I), $\bar{K}_3 < \bar{K}_4$ implies $\bar{K}_1 < \bar{K}_2$ and consequently it always holds $\bar{E}^{*} < \bar{E}^{**}$. Therefore, the classification of dynamic regimes in this sub-case coincides with that of case (I), showed in figures 1-3[28].

Sub-case II.2: $\gamma \leq \bar{\gamma}^{L}$

From figure 15, we can see that $\bar{K}_1 < \bar{K}_2$ implies $\bar{K}_3 < \bar{K}_4$ and consequently it always holds $\bar{E}^{*} > \bar{E}^{**}$. The dynamic regimes corresponding to this sub-case are showed in figures 4-6. As for the dynamics in (I) and (II.1), the stability properties of fixed points can be unambiguously inferred from arrow diagrams in figures 4-6.

Sub-case II.3: $\bar{\gamma}^{L} < \gamma < \bar{\gamma}^{U}$

It holds $\bar{E}^{*} < \bar{E}^{**}$ if and only if

$$\gamma > \bar{\gamma} \equiv \frac{\beta ab}{\left(\frac{(1+a)(1+b)}{1+a+d}\right)^{\frac{1}{1-\alpha}} - 1}$$

---

[26] See (15), (21).

[27] Remember that $\bar{\gamma}^{U} < \frac{\beta}{d} b(1 + a + d)$ always.

[28] Differently from the case I, in this case the slope of the curve $\dot{E} = 0$, under the curve (11), is negative. However, this feature makes no [qualitative] difference between the dynamic regimes of sub-case (II.1) and those of case (I) described in figures 1-3.

Remember that $\overline{E}^{*} < \overline{E}^{**}$ and $\overline{E}^{*} > \overline{E}^{**}$ for $\gamma \geq \overline{\gamma}^{U}$ and $\gamma \leq \overline{\gamma}^{L}$ respectively[29]; so, being $\overline{E}^{*}$ and $\overline{E}^{**}$ continuous functions of γ, by the *intermediate value theorem* it follows that $\overline{\gamma}^{L} < \overline{\gamma} < \overline{\gamma}^{U}$.

Dynamics can be classified as follows: If $\overline{E} > \overline{E}^{T}$, the dynamics is [qualitatively] the same as that depicted in figure 4; if $\overline{E}^{T} > \overline{E} > \max\left(\overline{E}^{*}, \overline{E}^{**}\right)$, the dynamics is that showed in figure 7; if $\overline{E}^{*} > \overline{E} > \overline{E}^{**}$ [$\gamma < \overline{\gamma}$], the dynamic regime is that represented in figure 5; if $\overline{E}^{**} > \overline{E} > \overline{E}^{*}$ [$\gamma > \overline{\gamma}$], the dynamics is the same as that in figure 2; finally, if $\overline{E} < \min\left(\overline{E}^{*}, \overline{E}^{**}\right)$, the dynamic regime is the same as that showed in figure 6.

[29] See cases (II.1) and (II.2).

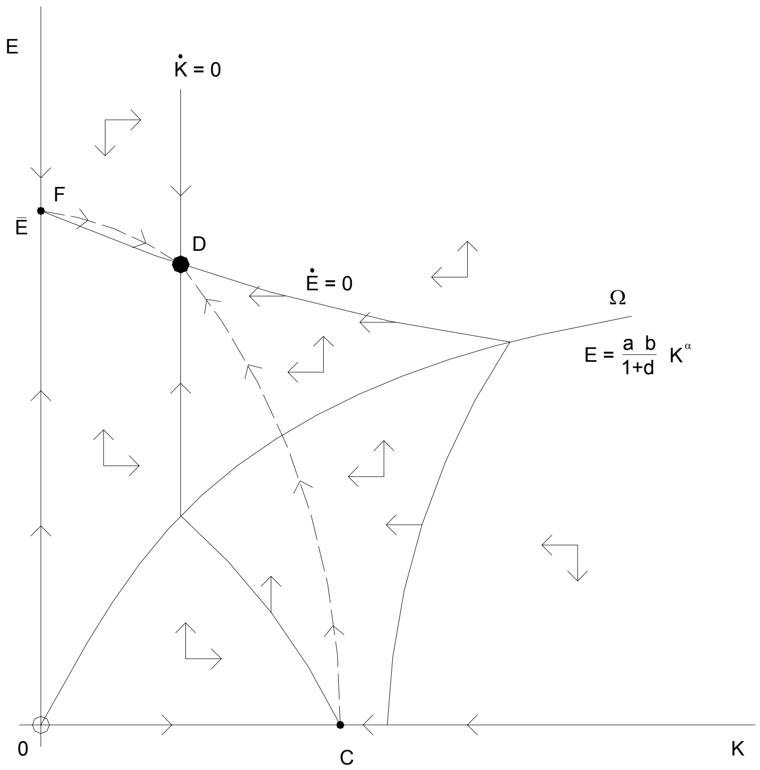

Figure 1

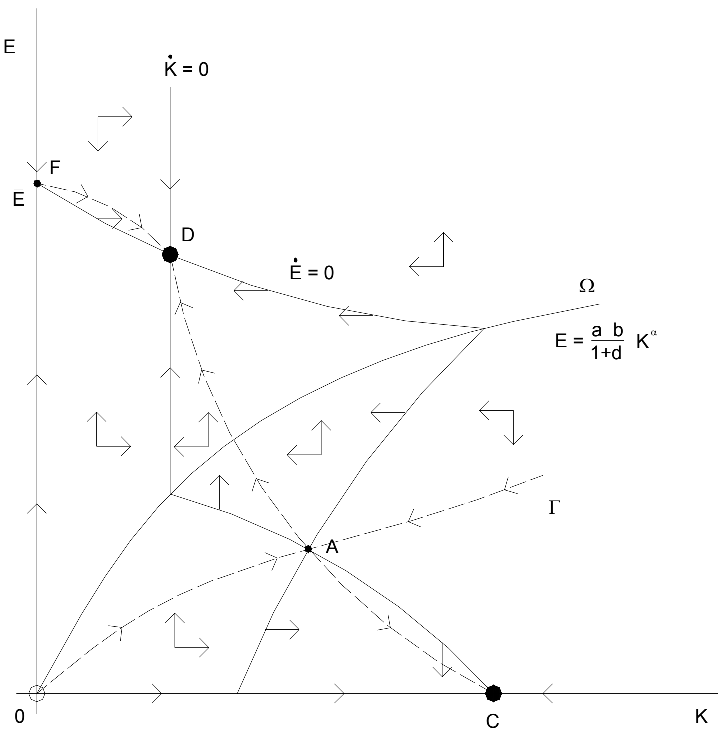

Figure 2

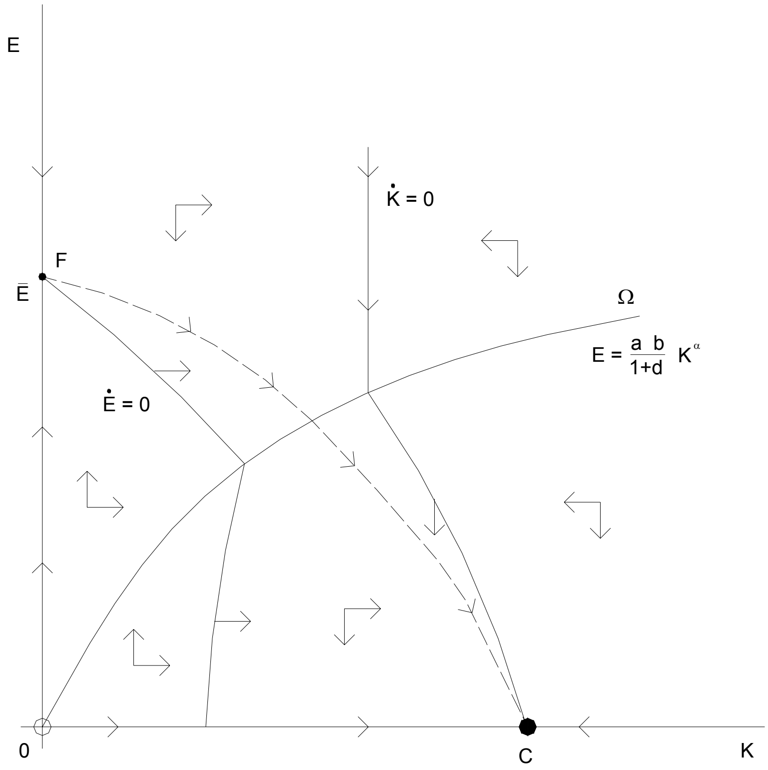

Figure 3

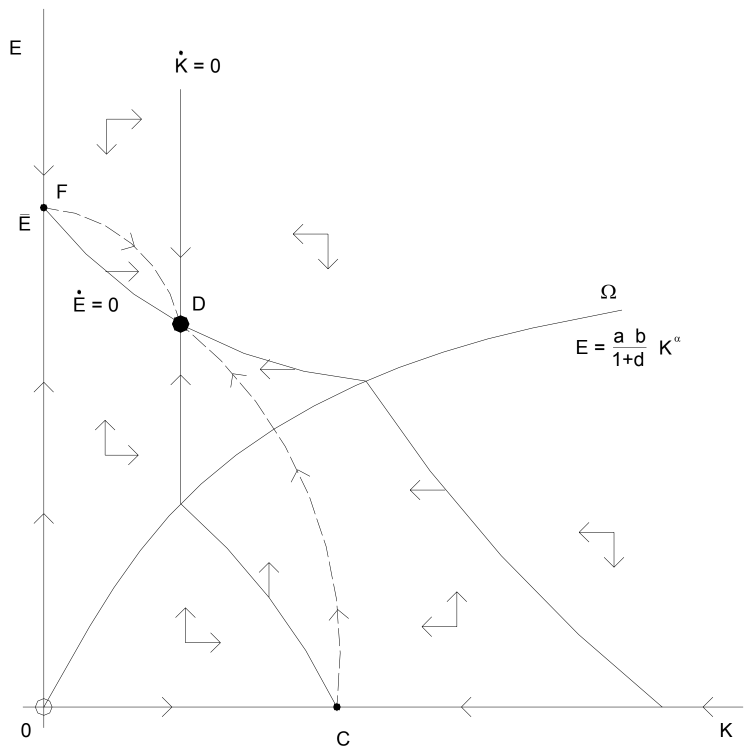

Figure 4

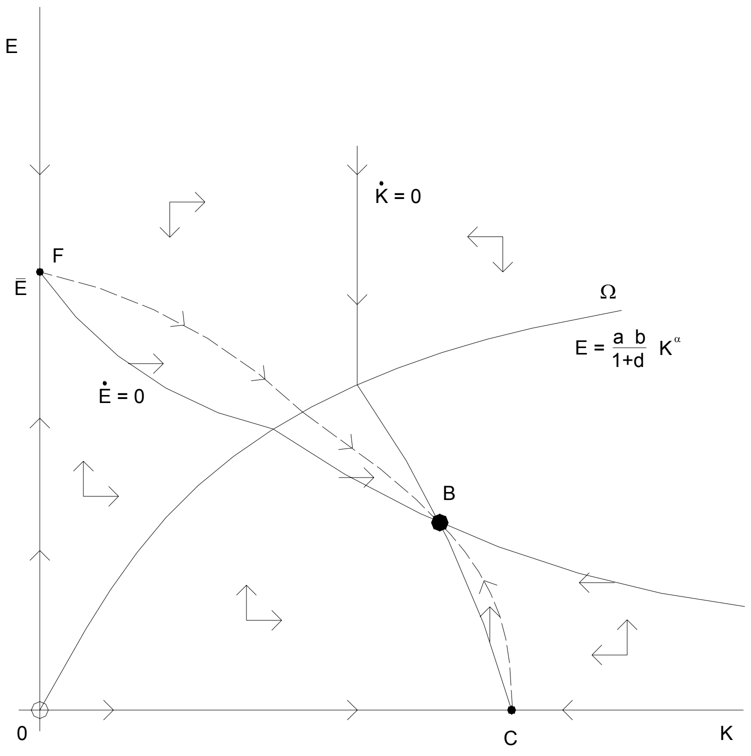

Figure 5

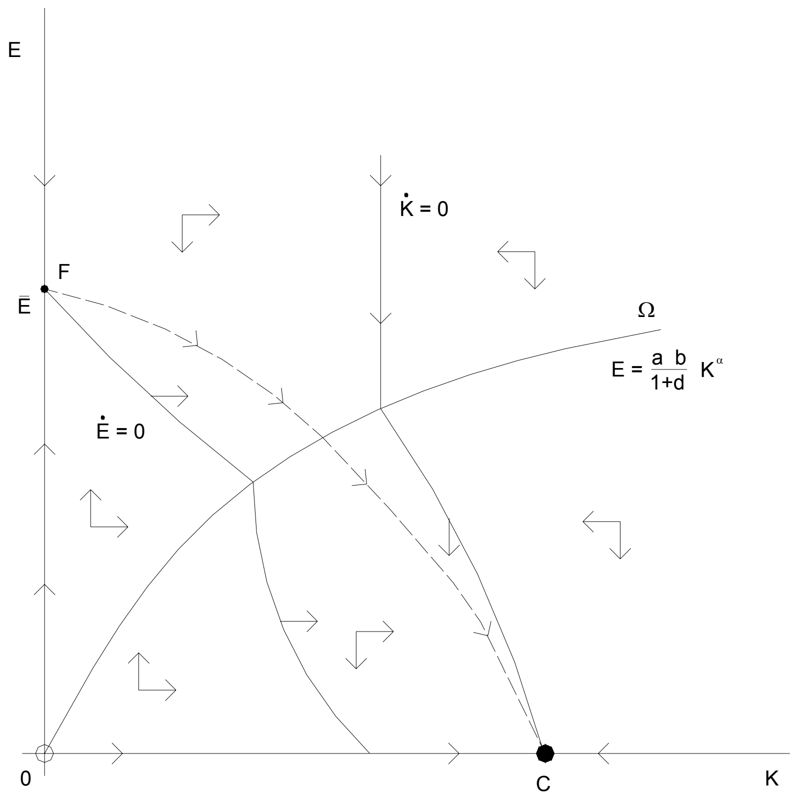

Figure 6

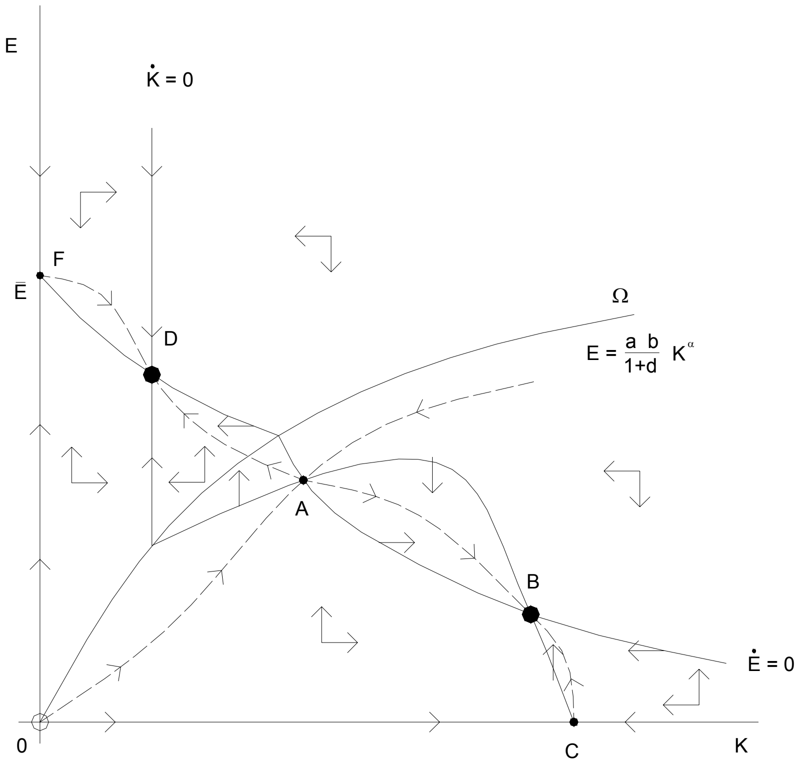

Figure 7

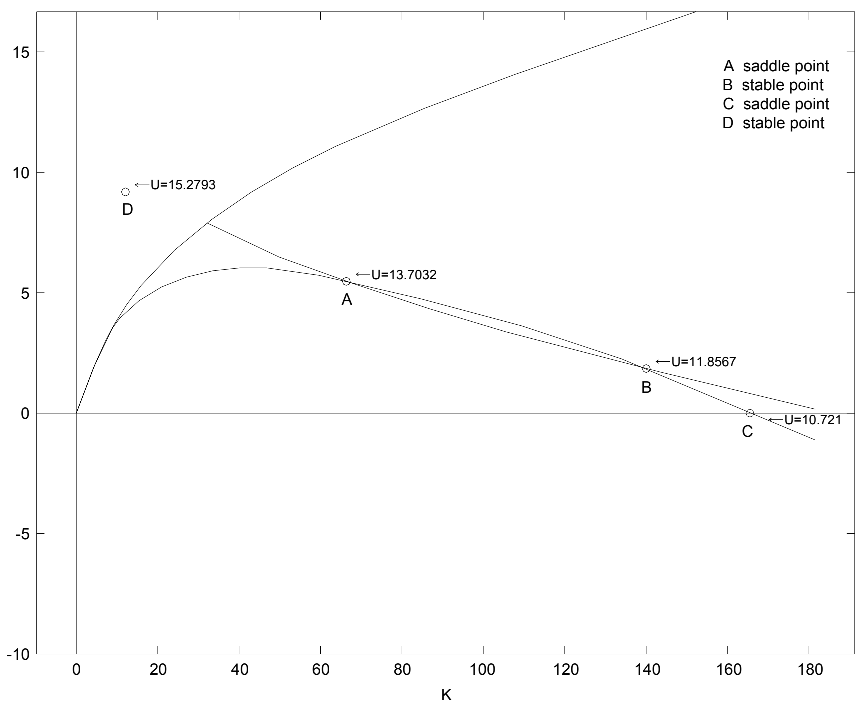

Figure 8: α=0.5, β=0.1, γ=0.1, η=0.05, a=8, b=1, d=5, $\bar{E}$=8.7

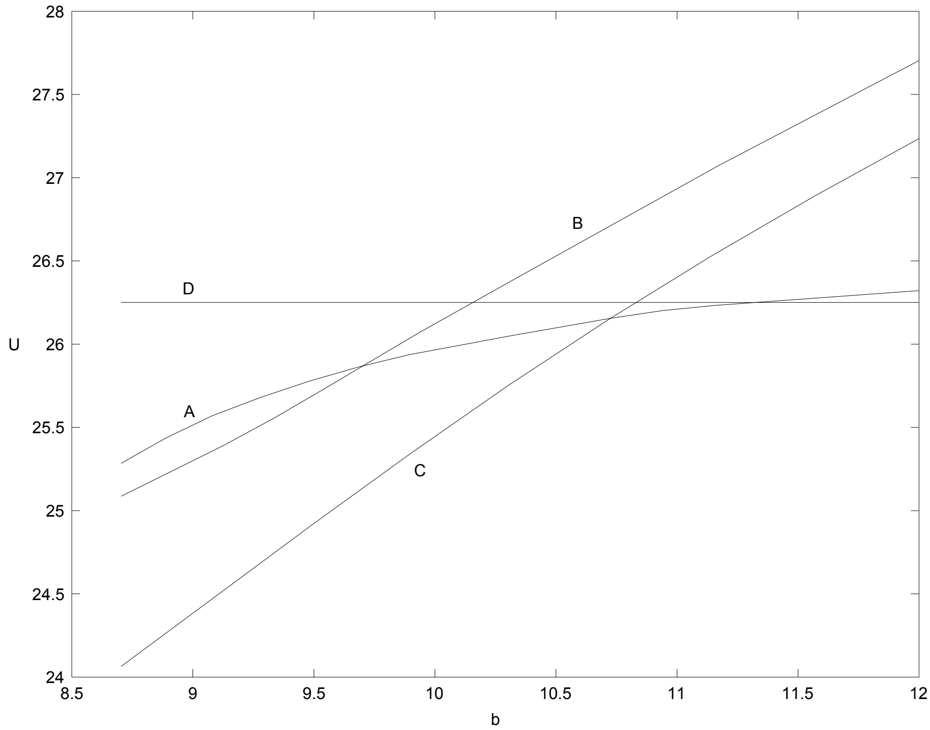

Figure 9: α=0.5, β=0. 01, γ=0.1, η=0.05, a=8, d=5, Ē=8.7

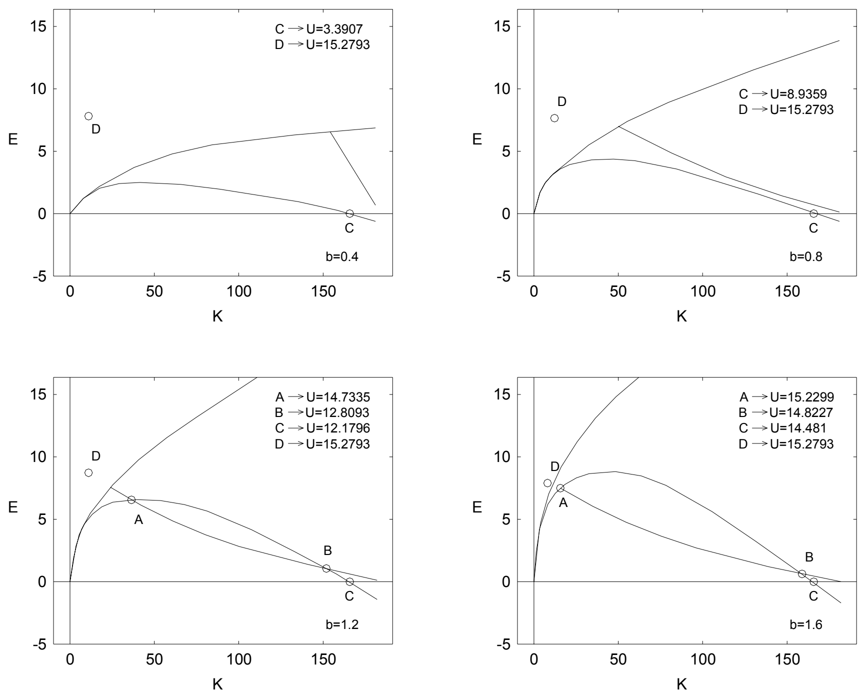

Figure 10: α=0.5, β=0. 1, γ=0.1, η=0.05, a=8, d=5, Ē=8.7

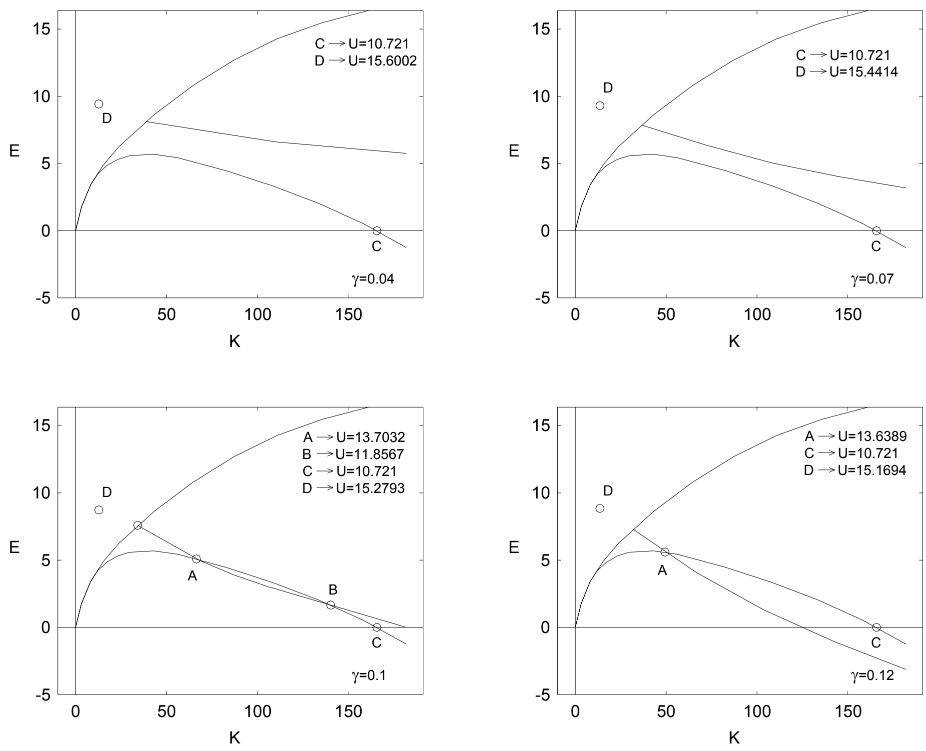

Figure 11: α=0.5, β=0.1, η=0.05, a=8, b=1, d=5, $\bar{E}$=8.7

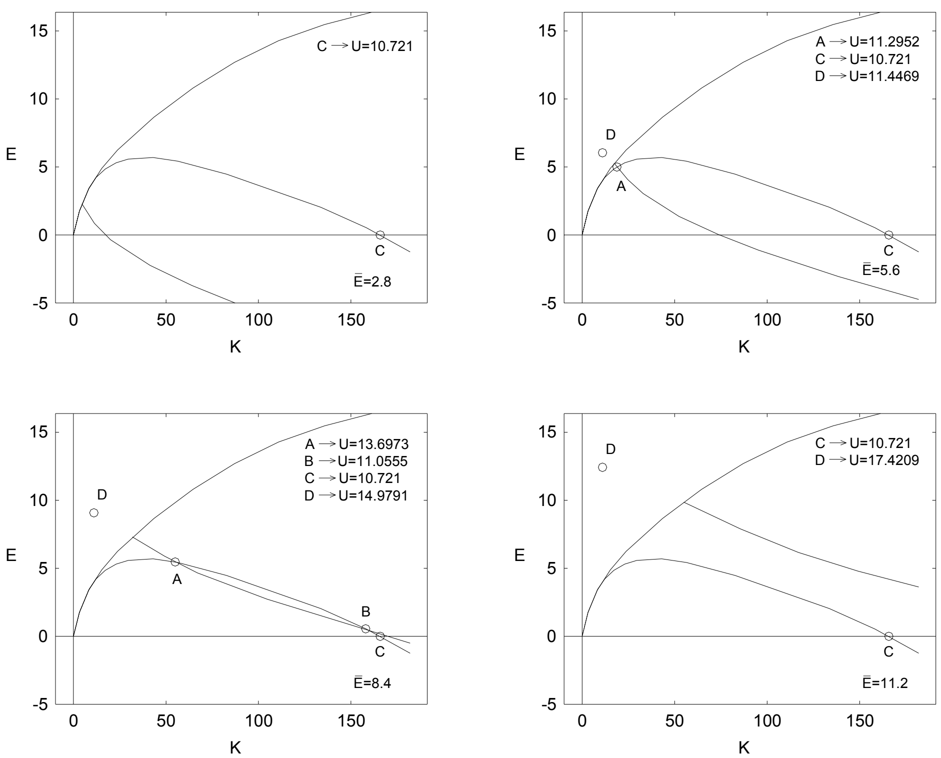

Figure 12: α=0.5, β=0.1, γ=0.1, η=0.05, a=8, b=1, d=5

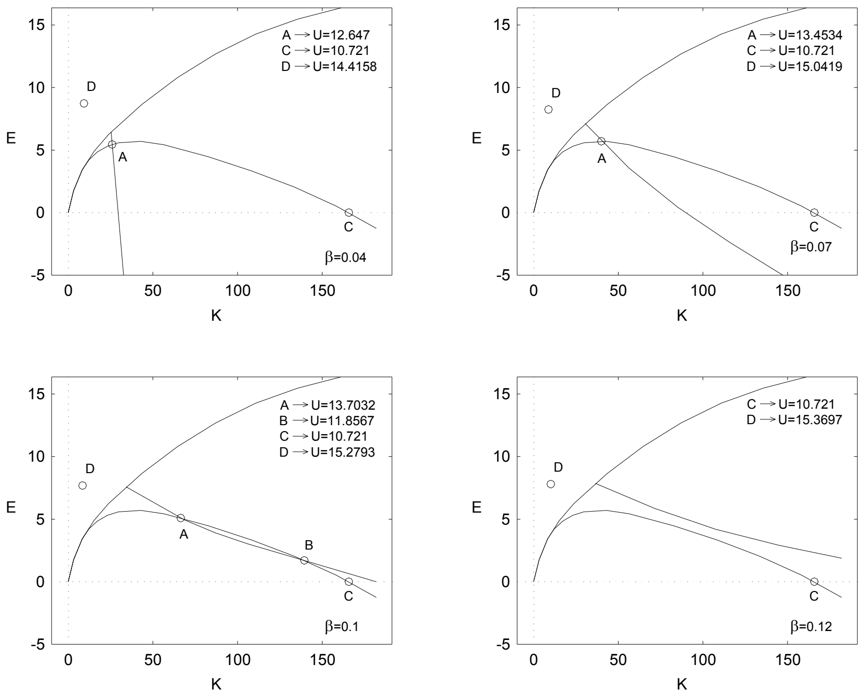

Figure 13: α=0.5, γ=0.1, η=0.05, a=8, b=1, d=5, $\bar{E}$=8.7

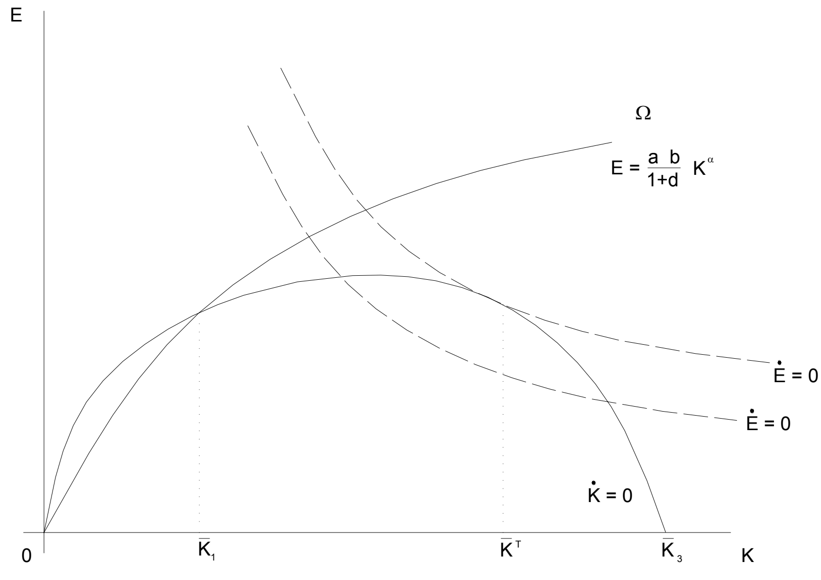

Figure 14

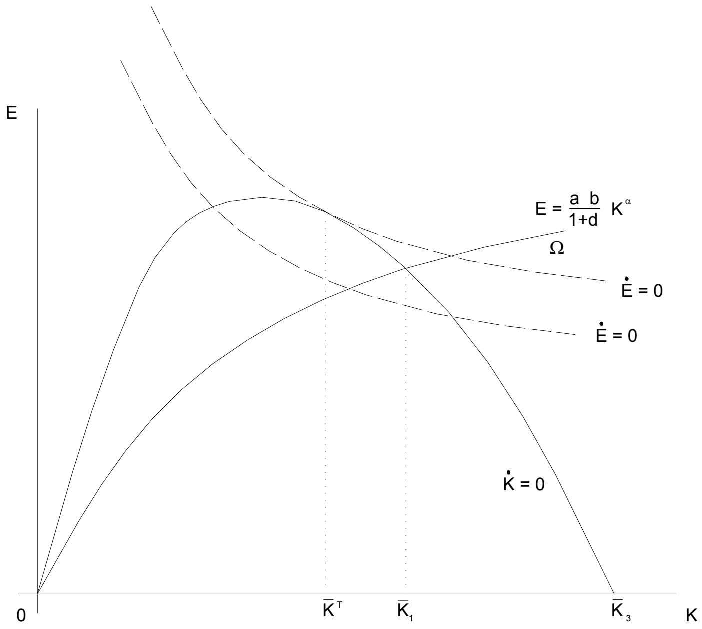

Figure 15

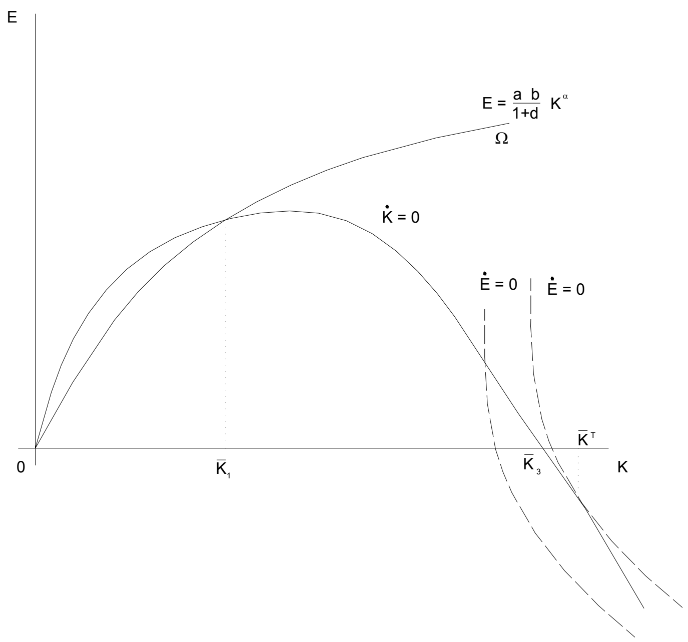

Figure 16

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(lxv) This paper was presented at the EuroConference on “Auctions and Market Design: Theory, Evidence and Applications” organised by Fondazione Eni Enrico Mattei and sponsored by the EU, Milan, September 25-27, 2003

(lxvi) This paper has been presented at the 4th BioEcon Workshop on “Economic Analysis of Policies for Biodiversity Conservation” organised on behalf of the BIOECON Network by Fondazione Eni Enrico Mattei, Venice International University (VIU) and University College London (UCL) , Venice, August 28-29, 2003

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