Nonlinear Dynamics in Economics, Finance and the Social Sciences

Essays in Honour of John Barkley Rosser Jr

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Structural Change, Economic Growth and Environmental Dynamics with Heterogeneous Agents

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1 Introduction

In many developing countries the asset distribution is highly concentrated and the economic agents differ not only by income, but also by their vulnerability to environmental depletion. The poor, especially in rural areas, tend to be more dependent on natural resources and more vulnerable to ecosystem degradation. Three quarters of the poor live in rural areas and more than half of the rural poor depend on breeding and agricultural activities: cultivation of staple food is the main source of calories, income and job for the rural poor (IFAD 2001). Moreover, it is commonly recognized that the rural poor in developing countries significantly rely on the common pool resources of the community they live in (Dasgupta (2001)), while according to World Resources Institute (2005) estimates, around 1 billion of the world poor rely in some way on forests (indigenous people wholly dependent on forests, smallholders who grow farm trees or manage remnant forests for subsistence and income). A meta-analysis of 54 case studies in developing countries found that the poor tend to be more dependent on forest environmental income than better-off households (Vedeld et al. 2004). Natural assets and common or free access resources provide the poor with other additional services: regulating production services such as flood, drought and erosion mitigation, soil renewal, soil fertility or the provision of food, fuelwood and energy and fresh water. Microeconomic studies confirm the relevance of the dependence of the rural population on the community or free access resources (Beck and Nesmith 2001; Cavendish 2000; Falconer 1990; Fisher 2004; Jodha 1986; Narain et al. 2005). On the other hand, the rich have a greater ability to substitute private goods for environmental goods. They are thus able to protect themselves from pollution and to face the depletion of natural capital (United Nations Environment Programme 2004).

Against this background, we analyze a model that considers an economy with two sectors: a traditional resource-based sector that relies on self-employment of

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poor households and a sector managed by the rich. Physical capital is completely concentrated in the endowments of the rich, while all agents -poor and rich- have access to environmental capital. The polarization of society into two sectors and two classes of agents is clearly an oversimplification, but this assumption makes the model tractable using standard methodology. Moreover, although we consider a highly stylized context, it reflects the ways in which different assets (natural, physical, social, human capital) are typically distributed in several developing countries. Physical capital tends to have a concentrated dispersion across the population because of financial market failures. In absence of perfect information and competition, wealthier individuals and large firms have privileged access to capital market, because they are more endowed with collateral and have a higher ability to exploit scale economies. Conversely, services deriving from environmental resources may be more dispersed and tend to have the characteristics of public goods (in our model all agents have access to environmental capital). In this context, economic agents also differ by feed-back mechanisms and interaction between their production (consumption) choices and environmental dynamics.

In this setting, we show that economic dynamics are path dependent in that the model admits a multiplicity of stable steady states. Furthermore, the model may exhibit a zero-sum game structure. Physical capital endowments allow the Rich to employ wage labor and this possibility is the root of the difference between the rich (labor employers) and the poor (labor force providers) in terms of vulnerability to environmental degradation. The rich are more able to defend themselves from environmental degradation because they can partially substitute natural capital with physical capital or wage labor employment. Thus, the rich may be not disadvantaged by the environmental degradation because they can rely on substitution possibilities as a defensive strategy. To the contrary, they may benefit from the role played by the natural capital scarcity in accelerating labor movement from the traditional to the modern sector. This, in turn, generates incentives to physical capital accumulation. On the other hand, the poor are disadvantaged because they face a reduction in productivity of their labor, namely, in their greatest means of subsistence.

In the history of the development theory, structural change, i.e. the movement of a labor force from the traditional resource-based to the modern sector, is regarded by some economists as a cause and consequence of economic development and growth (see e.g. Lewis 1955; Lucas 2004; Ranis and Fei 1961): growth of the non-resource sectors may permit an unending process of labor productivity growth because they rely on assets (human capital and physical capital) that can expand over time. Saving and investment in physical capital can produce an increase in labor productivity leading to economic expansion. In a dual framework, such vision implies that capital intensive activities are able to sustain a process of economic growth, while the production of the subsistence sector is constrained and cannot overcome a certain threshold because it relies on limited production factors. Therefore a labor shift towards the "modern" sector leads to a structural change associated with an increase of social welfare. Conversely, in our model, structural changes may be "perverse" in the sense of López (2003, 2007), i.e. associated with growing problems of poverty and environmental degradation. Pressures on natural resources can cause a decline in productivity of traditional agricultural activities and the consequent reduction of labor opportunity costs fuels a labor migration from the agricultural sector. The result is a movement of the labor force from the traditional resource-based to the modern sector associated with declining or stagnant wages and with a loss of welfare for labor force.[1]

The remainder of the article is organized as follows. Sections 2 and 3 present the model. Section 4 analyzes the model and investigates some possible dynamics that may emerge and their implications in terms of welfare. Section 5 draws conclusions. A mathematical appendix concludes the paper.

2 The Dual Context

We consider a small open economy[2] with three production factors: labor, a free access renewable natural resource (E) and physical capital (K). In this economy, agents belong to two different populations: the "Rich" (R-agents) and the "Poor" (P-agents). The R-agents accumulate physical capital, hire the labor force and employ all their potential work - represented by a fixed amount of entrepreneurial activity - to produce a storable private good. We call their production "capitalistic sector" or "modern sector". The P-agents are endowed only with labor and they have to choose the distribution of their labor between two activities: working as employees of the Rich in the capitalistic sector or directly exploiting natural resources to produce a non storable good. Let "subsistence sector" or "traditional sector" denote production of the Poor. Given that the Poor cannot invest and accumulate physical capital, we assume that the capital market is completely segmented and is accessible only by the Rich.

The population of the Poor is constituted by a continuum of identical individuals and the size of the population is represented by the positive parameter $\overline{N}$. The P-population's welfare depends on two goods:

1. A non storable good deriving directly from free access renewable natural resources, hereafter referred to as an environmental good.

[1] López points out that indirect factors capable of triggering a perverse structural change are inadequate policies aimed at fostering productivity in the modern sector in addition to a complete neglect of the traditional subsistence sector of the rural poor.

[2] The majority of developing countries are little open economies. In the last two decades, several countries have undertaken trade liberalization reforms and, consequently, the importance of the domestic demand in sustaining economic growth has diminished (at least for trade sectors) because economies are less constrained by limited national demand. To the contrary in open economies, a fundamental factor for economic growth is productive competitiveness that depends on, among other important factors, labour cost. In this sense, Matsuyama's model (Matsuyama 1992) is particularly explicative because it shows how the growth process might be driven by different factors in an open and a closed context: he finds a negative relationship between agricultural productivity and economic growth in open economies, while detecting the inverse links in closed economies.

2. A good (hereafter denoted private good) which can be consumed as a substitute for the services coming from the environmental good.

We assume that the instantaneous utility function of each P-agent is the following

$$U_P(c_P, c_S) = \ln(c_P + ac_S), \tag{1}$$

where:

c_S is the consumption of the produced good as a substitute for the environmental good.
c_P is the consumption deriving from the exploitation of the environmental resource.

According to (1), c_S and c_P are perfect substitutes, with a (constant) rate of substitution equal to $a > 0$. That is, the private good produced by the Rich is able to substitute completely c_P. This is a stylized fact, but it can represent the main components of poor people's welfare: if they work in the subsistence sector in rural areas (fishing, forestry, agriculture or breeding) their living standard strictly depends on their access to and exploitation of E; while if they move to urban zones or they become a wage labor force, they satisfy their needs mainly through the consumption of private goods.

Each P-agent, in each instant of time, employs all his potential labor (that we normalize to unity) in the subsistence sector or in the sector of the Rich. Thus, he cannot rely on alternative income sources at the same time. However, in the absence of inter-sectorial moving costs, significant divergences from the case with employment diversification are not a priori expected. Therefore, for the sake of analytical simplicity, the hypothesis of indivisible labor allocation will be retained.

Let us indicate with N_P and N_R the number of Poor that work, respectively, in the subsistence sector and in the capitalist sector. Consequently, we have $N_P + N_R = \overline{N}$. The aggregate function of production in the traditional sector is given by[3]

$$Y_P = \alpha N_P E.$$

We have assumed that the Poor cannot save and that production is completely exhausted by their consumption. From this equation, it follows that per capita output and consumption of the Poor working in this sector is equal to

$$c_P = \frac{Y_P}{N_P} = \alpha E. \tag{2}$$

The Poor that are hired in the market goods sector receive a real wage equal to w (in terms of the private good produced by the Rich) that is considered as exogenously

[3] This specification was proposed by Schaefer (1957) for fishery and since then it has been widely adopted in literature in modelling natural resources (see e.g. Brander and Taylor 1998a,b; Conrad 1995; López et al. 2007; McAusland 2005; Munro and Scott 1993).

given. By (1), the Poor are indifferent between work in the traditional sector and in the capitalistic sector if and only if

$$c_P = ac_S = aw \tag{3}$$

which can be re-expressed as

$$\frac{1}{a}\alpha E = w. \tag{4}$$

If $\frac{1}{a}\alpha E > w$ (respectively, $\frac{1}{a}\alpha E < w$), then no Poor (respectively all Poor, i.e. $\overline{N}$) would like to work in the capitalistic sector. We assume that E is taken as exogenously given by the Poor, that is, they do not internalize the impact of their production on natural resources; however, we will return to this issue later. In (4), the parameter a determines the difference between the wage in the capitalistic sector and the average output in the traditional sector that allows for the same level of utility.

The population of the Rich is constituted by a continuum of identical individuals and the size of the population is represented by the positive parameter $\overline{M}$. We normalize the size of the R-population by assuming $\overline{M} = 1$. As said, the representative R-agent employs all his fixed potential labor in the modern sector as entrepreneurial activity. Without loss of plausibility, we assume that the marginal product of entrepreneurial labor in the modern sector is higher than the marginal product of labor in the subsistence sector. Therefore, the possibility that the Rich work in the subsistence sector is excluded a priori and the production function of the modern sector can be specified as follows

$$Y_R = \beta K^{\gamma} E^{\delta} (N^D)^{1-\gamma-\delta},$$

where:

- $\gamma > 0$, $\delta \geq 0$ and $\gamma + \delta < 1$ (i.e. the production function satisfies the constant returns to scale assumption).
- K is the physical capital accumulated by the representative R-agent.
- N^D is labor demand by the representative R-agent.
- β is a positive parameter representing (exogenous) technical progress.

3 Economic Dynamics

P and R-agents consider the effect of their choices on the environment as negligible and they do not internalize it; therefore, in their maximization problems they take the evolution of E as given; that is, they behave without taking into account the shadow value of the natural resource and so nobody has an incentive to preserve or restore natural resources. Thus, investment in natural capital does not affect the environmental stock; the dynamics of E is given by the usual logistic function modified for human intervention

$$\dot{E} = E(\overline{E} - E) - \epsilon\alpha N_P E - \eta\overline{Y}_R, \tag{5}$$

where:

- $\overline{E}$ is the carrying capacity of the environmental resource, that is, the maximum stock at which E stabilizes in absence of negative impacts due to P and R-agents' economic activities.
- $\epsilon\alpha N_P E$ is the aggregate environmental impact by the subsistence sector and the parameter $\epsilon > 0$ represents the exploitation of the natural resource by P-agents.
- $\eta > 0$ is a parameter measuring the environmental deterioration caused by the average production $\overline{Y}_R$ of R-agents.

Since there is no investment in natural capital, the R-agent invests in physical capital accumulation everything he saves after consumption expenditures and remuneration of the employed labor force. Therefore the stock of physical capital grows according to the following equation

$$\dot{K} = \beta K^\gamma E^\delta (N^D)^{1-\gamma-\delta} - wN^D - c_R. \tag{6}$$

Preferences of the Rich are assumed to be representable by a utility function defined over the consumption of the private good. Let the R-agent's instantaneous utility be

$$U_R(c_R) = \ln c_R.$$

Therefore U_R is twice continuously differentiable, strictly increasing and strictly concave, that is $U_R' > 0$ and $U_R'' < 0$. The representative R-agent maximizes his utility by choosing c_R and the labor demand N^D, that is, he solves the following intertemporal optimization problem

$$\underset{c_R,\, N^D}{Max} \int_0^\infty (\ln c_R) e^{-rt} dt$$

under the constraints (5) and (6), where $r > 0$ is the discount rate. The solution to the R-agent's problem is found considering the following current value Hamiltonian function

$$H = \ln c_R + \lambda(\beta K^\gamma E^\delta (N^D)^{1-\gamma-\delta} - wN^D - c_R) + \theta(E(\overline{E} - E) - \epsilon\alpha N_P E - \eta\overline{Y}_R),$$

where λ and θ are the co-state variables associated to K and E, respectively. It is easy to verify that the dynamics of K, E and λ, do not depend on θ. In fact, we have assumed that agents consider $\epsilon\alpha N_P E$ and $\overline{Y}_R$ as given in the maximization problem above and consequently the resulting dynamics are not optimal; however, the trajectories under such dynamics are Nash equilibria (see Wirl, 1997), in the sense that no (Rich or Poor) agent has an incentive to modify his choices along each trajectory generated by the model as long as the others do not modify theirs. The dynamics generated by the model are found by applying the maximum principle

$$\begin{aligned}
\dot{K} &= \frac{\partial H}{\partial \lambda} = \beta K^{\gamma} E^{\delta} (N^D)^{1-\gamma-\delta} - w N^D - c_R, \\
\dot{E} &= \frac{\partial H}{\partial \theta} = E(\overline{E} - E) - \epsilon \alpha N_P E - \eta \overline{Y}_R, \\
\dot{\lambda} &= r\lambda - \frac{\partial H}{\partial K} = \lambda \left[r - \beta \gamma K^{\gamma-1} E^{\delta} (N^D)^{1-\gamma-\delta} \right],
\end{aligned}$$

where c_R, N^D and N_P are determined by the following conditions

$$\frac{\partial H}{\partial c_R} = \frac{1}{c_R} - \lambda = 0 \qquad (\text{i.e. } c_R = \frac{1}{\lambda}),$$

$$\frac{\partial H}{\partial N^D} = \lambda(\beta(1-\gamma-\delta) K^{\gamma} E^{\delta} (N^D)^{-\gamma-\delta} - w) = 0,$$

that is

$$\beta(1-\gamma-\delta) K^{\gamma} E^{\delta} (N^D)^{-\gamma-\delta} = w. \tag{7}$$

The labor market is perfectly competitive and wage is flexible. The equilibrium value of N_P is given by the labor market equilibrium condition [obtained by equalizing the left sides of (4) and (7)]

$$\frac{\alpha}{a} E = \beta(1-\gamma-\delta) K^{\gamma} E^{\delta} (\overline{N} - N_P)^{-\gamma-\delta}.$$

In particular, we obtain

$$N_P = \overline{N} - \left[\frac{a\beta(1-\gamma-\delta)}{\alpha} \right]^{\frac{1}{\gamma+\delta}} E^{-\frac{1-\delta}{\gamma+\delta}} K^{\frac{\gamma}{\gamma+\delta}} \tag{8}$$

if the right side of (8) is not negative, otherwise $N_P = 0$ (i.e. $\overline{N}$ Poor work in the capitalistic sector). By substituting $N_P = 0$ in (8) and solving it with respect to K we obtain the curve that separates the region where $N_P > 0$ from that where $N_P = 0$ in the plane (E, K)

$$K = L(E) := \left[\frac{\alpha \overline{N}^{\gamma+\delta}}{a\beta(1-\gamma-\delta)} \right]^{\frac{1}{\gamma}} E^{\frac{1-\delta}{\gamma}}, \tag{9}$$

where $\dfrac{1-\delta}{\gamma} > 1$.

Along and above the curve (9), $N_P = 0$ holds. By substituting N^D with the equilibrium value of $\overline{N} - N_P$ in (7) the equilibrium wage w is found.

Finally, given that (ex-post) $\overline{Y}_R$ is equal to Y_R, the dynamics generated by the model are the following

$$\dot{K} = \beta(\gamma + \delta)K^\gamma E^\delta (\overline{N} - N_P)^{1-\gamma-\delta} - \frac{1}{\lambda}, \tag{10}$$

$$\dot{E} = E(\overline{E} - E) - \epsilon\alpha N_P E - \eta\beta K^\gamma E^\delta (\overline{N} - N_P)^{1-\gamma-\delta}, \tag{11}$$

$$\dot{\lambda} = \lambda(r - \beta\gamma K^{\gamma-1} E^\delta (\overline{N} - N_P)^{1-\gamma-\delta}), \tag{12}$$

where $N_P = 0$ for (E, K) above (9) while N_P is given by (8) for (E, K) below the curve (9). The following restrictions on variables and parameters hold: K, E, $\lambda > 0$; $a, \alpha, \beta, \gamma, \epsilon, \eta, r, \overline{E}, \overline{N} > 0$; $\delta \geq 0$, $\gamma + \delta < 1$.

4 Analysis of the Model

In this section we analyze the existence and stability of the fixed points (i.e. the stationary states) of the model dynamics, obtained by imposing $\dot{E} = 0$, $\dot{K} = 0$, $\dot{\lambda} = 0$ in the system (10)–(12). Note that, for $\lambda > 0$, equations $\dot{E} = 0$ and $\dot{\lambda} = 0$ depend only on E and K and consequently, solving them, we obtain the fixed point values of E and K. The corresponding value of λ is obtained by solving the equation $\dot{K} = 0$.

4.1 The Case Without Specialization

In the case without specialization (i.e. $\overline{N} > N_P > 0$), the condition $\dot{E} = 0$ is satisfied along the graph of the function

$$K = F(E) := E^{\frac{1-\delta}{\gamma}} \left(\frac{\overline{E} - E - \epsilon\alpha\overline{N}}{M(\beta\eta M^{-\gamma-\delta} - \epsilon\alpha)} \right)^{\frac{\gamma+\delta}{\gamma}},$$

where $M := \left(\frac{a\beta(1-\gamma-\delta)}{\alpha} \right)^{\frac{1}{\gamma+\delta}}$, and the condition $\dot{\lambda} = 0$ is satisfied along the graph of the function

$$K = G(E) := \left(\frac{\beta\gamma}{r} M^{1-\gamma-\delta} \right)^{\frac{\gamma+\delta}{\gamma}} E^{\frac{2\delta+\gamma-1}{\delta}}.$$

Therefore, the intersections between $F(E)$ and $G(E)$ (occurring below the curve (9)) identify the fixed points under the regime of no specialization. To state the existence and stability results on these fixed points, we define

$$\Omega := \alpha \left(\frac{\eta}{a(1-\gamma-\delta)} - \epsilon \right),$$

$$\Delta := \frac{r}{\beta\gamma \left(\frac{a\beta(1-\gamma-\delta)}{\alpha} \right)^{\frac{1-\gamma}{\gamma}}},$$

$$\overline{N}_1 := \frac{1}{\Delta^{\frac{\gamma}{1-\gamma}}} \left[\frac{\delta a}{\alpha[\eta - \epsilon a(1-\gamma-\delta)]} \right]^{\frac{1-\gamma-\delta}{1-\gamma}},$$

$$\overline{E}_1 := \frac{\left(1 + \frac{\delta}{1-\gamma-\delta}\right)}{\left[\left(\overline{N}_1\right)^{\delta} \Delta^{\gamma}\right]^{\frac{1}{1-\gamma-\delta}}} + \alpha\epsilon\overline{N},$$

$$\overline{E}_2 := \frac{\alpha\eta\overline{N}}{1-\gamma-\delta} + \left(\frac{1}{\overline{N}^{\delta}\Delta^{\gamma}} \right)^{\frac{1}{1-\gamma-\delta}}.$$

According to the sign of Ω, two regimes can be distinguished:

1. REGIME DCS (Dirty Capitalistic Sector). *We denote regime DCS (Dirty Capitalistic Sector) as the scenario in which η, the rate of environmental impact caused by the capitalistic sector, is relatively high (ceteris paribus) in comparison to the environmental impact of the traditional sector, measured by ε. That is, $\Omega > 0$ holds, where $\Omega > 0$ if and only if $\frac{\eta}{\epsilon} > a(1-\gamma-\delta)$.*
2. REGIME DTS (Dirty Traditional Sector). *We denote regime DTS (Dirty Traditional Sector) as the scenario in which: $\Omega < 0$.*

Now we can state the following proposition. The proof of such a proposition requires straightforward but tedious calculations; due to space constraints, we will therefore omit it.[4]

[4] The proof is available from the authors on request.

Proposition 1. *In the regime DCS (i.e. $\Omega > 0$), two fixed points with $\overline{N} > N_P > 0$ at most exist. In particular, two fixed points exist if*

$$\overline{N} > \overline{N}_1, \quad \overline{E}_1 < \overline{E} < \overline{E}_2.$$

One fixed point exists if

$$\overline{N} \geq \overline{N}_1, \quad \overline{E} \geq \overline{E}_2.$$

No fixed point exists in the remaining cases.

In the regime DTS (i.e. $\Omega < 0$), one fixed point with $\overline{N} > N_P > 0$ at most exists. In particular, it exists if

$$\overline{E} \geq \overline{E}_2.$$

No fixed point exists in the remaining cases.

In the regime DCS (i.e. $\Omega > 0$), if two fixed points exist, in one of these the curve $G(E)$ intersects $F(E)$ from above in the plane (E, K) (we will indicate such a point with the letter A) while in the other point (which we will indicate with B) the opposite holds; in A the value of E is lower than in B. If only one fixed point is admissible, its configuration is like a point B, namely in it $G(E)$ intersects $F(E)$ from below (see Fig. 6 of the mathematical appendix). In the regime DTS (i.e. $\Omega < 0$), in the unique fixed point the curve $G(E)$ intersects $F(E)$ from above.

Proposition 1 highlights that the fixed points with $\overline{N} > N_P > 0$ exist only when the carrying capacity $\overline{E}$ overcomes certain thresholds ($\overline{E} \geq \overline{E}_1$ if $\Omega > 0$ and $\overline{E} \geq \overline{E}_2$ if $\Omega < 0$). These thresholds are positively correlated to the rate of environmental impact caused by the two sectors (ϵ and η). Thus, if the economic activities are too polluting then stationary points with $\overline{N} > N_P > 0$ do not exist.

Proposition 1 also implies that $\overline{E}$ or $\overline{N}$ can always be found so that two fixed points exist if $\Omega > 0$ and one fixed point exists if $\Omega < 0$, namely the maximum number of admissible stationary points.

Let (E^*, K^*, λ^*) denote the fixed point value of the variables. The stability properties of fixed points depend on the signs of the real parts of the eigenvalues associated to the Jacobian matrix J of the dynamic system (10)–(12) evaluated in (K^*, E^*, λ^*). We define "saddle-point stable" a fixed point that has two eigenvalues with negative real parts, i.e. with a two-dimensional stable manifold. As a matter of fact, under the perfect foresight assumption, if the fixed point has a two-dimensional stable manifold, given the initial values $K(0)$ and $E(0)$ of the state variables K and E, R-agents are able to fix the initial value $\lambda(0)$ of the jumping variable λ so that the growth trajectory starting from $(E(0), K(0), \lambda(0))$ approaches the fixed point. Therefore the fixed point can be reached by growth trajectories. If the fixed point has less than two eigenvalues with negative real parts, then given the initial values $K(0)$ and $E(0)$, a value $\lambda(0)$ does not (generically) exist so that the growth trajectory starting from $(K(0), E(0), \lambda(0))$ approaches the fixed point.

Proposition 2. *The fixed points without specialization ($\overline{N} > N_P > 0$) are characterized by the following stability properties:*

In the regime DCS (i.e. $\Omega > 0$), the fixed point A has always two eigenvalues with positive real parts. The fixed point B is always saddle-point stable if $\gamma + 2\delta - 1 < 0$ while, if $\gamma + 2\delta - 1 > 0$, it can be saddle-point stable or repulsive; however, if $E^* > \frac{1}{2}\left(\overline{E} - \epsilon\alpha\overline{N} - \frac{r\delta}{\gamma}\right)$, it is saddle-point stable.

In the regime DTS (i.e. $\Omega < 0$), the unique fixed point is always saddle-point stable.

Proof. See appendix.

From Proposition 2, it follows that if the gap between the value of the parameter $\overline{E}$ - denoting the carrying capacity - and E^* is not too wide (namely if $E^* > \frac{1}{2}(\overline{E} - \epsilon\alpha\overline{N} - \frac{r\delta}{\gamma})$), the fixed point B is saddle-point stable. As we will see in the following sections, this gap depends on demographic pressure and on the environmental impact of the production of the Poor and the Rich because E^* is decreasing in ϵ, η and $\overline{N}$. As long as the parameters ϵ, η and $\overline{N}$ overcome a certain threshold, the gap is such that the fixed point cannot be reached.

4.2 The Case with Specialization $N_P = 0$

In this context, the condition $\dot{E} = 0$ is satisfied along the graph of the function

$$K = F_0(E) := \frac{E^{\frac{1-\delta}{\gamma}}(\overline{E} - E)^{\frac{1}{\gamma}}}{(\eta\beta\overline{N}^{1-\gamma-\delta})^{\frac{1}{\gamma}}}$$

while the condition $\dot{\lambda} = 0$ is satisfied along the graph of the function

$$K = G_0(E) := \left(\frac{\beta\gamma}{r}\overline{N}^{\frac{1}{\gamma}}\right)^{\frac{1}{1-\gamma}} E^{\frac{\delta}{1-\gamma}}.$$

Therefore the intersections between $F_0(E)$ and $G_0(E)$ identify the fixed points under the regime of perfect specialization in the production of the capitalistic sector.

To state the following proposition, we define

$$\Gamma := \frac{1-\gamma-\delta}{2-2\gamma+\delta},$$

$$\overline{E}_0 := \left(\frac{\overline{N}}{\Gamma}\right)^{\theta}\left(\frac{\left(\frac{\beta\gamma}{r}\right)^{\frac{1}{1-\gamma}}}{\frac{\gamma}{\eta r}(1-\Gamma)}\right)^{\frac{1-\gamma}{2-2\gamma-\delta}},$$

$$\overline{N}_0 := \frac{r\eta}{\gamma}(1-\Gamma)\left(\frac{\beta\gamma}{r}\right)^{\frac{1}{\gamma}}\left(\frac{\alpha\eta\Gamma^{\Gamma}}{a(1-\Gamma)(1-\gamma-\delta)}\right)^{\frac{2\gamma+\delta-1}{1-\gamma}}.$$

With straightforward calculations, we can prove that:[5]

Proposition 3. *Two fixed points with $N_P = 0$ at most exist. In particular, two fixed point exist if*

$$\overline{N} < \overline{N}_0, \quad \overline{E}_0 < \overline{E} < \overline{E}_2.$$

One fixed point exists if

$$\overline{E} \geq \overline{E}_2.$$

No fixed point exists in the remaining cases.

When two fixed points with specialization exist, in one of these points (the fixed point that we will denote with A_0) the graph of $G_0(E)$ intersects that of $F_0(E)$ from above, viceversa in the other fixed point (which we will indicate with B_0) Furthermore, in A_0 the value of E is lower than in B_0. If only one fixed point exists, its configuration is like a point A_0 namely in this point $G_0(E)$ intersects $F_0(E)$ from above (see Fig. 7 of the mathematical appendix).

Proposition 4. *The fixed point A_0 has always two eigenvalues with positive real parts, while B_0 can be saddle-point stable; in particular, it is the case if*

$$E^* > \frac{1}{2}\left(\overline{E} - \frac{r}{\gamma(1-\gamma)}\right).$$

Proof. See appendix.

According to Proposition 4, E^* has to be sufficiently high for saddle-point stability, i.e. $E^* > \frac{1}{2}\left(\overline{E} - \frac{r}{\gamma(1-\gamma)}\right)$. These are sufficient conditions so that the system presents a saddle-point stable stationary state with disappearance of the traditional sector and a complete process of "proletarianization" with all the Poor employed in capitalistic production.

[5] The proof is available from the authors on request.

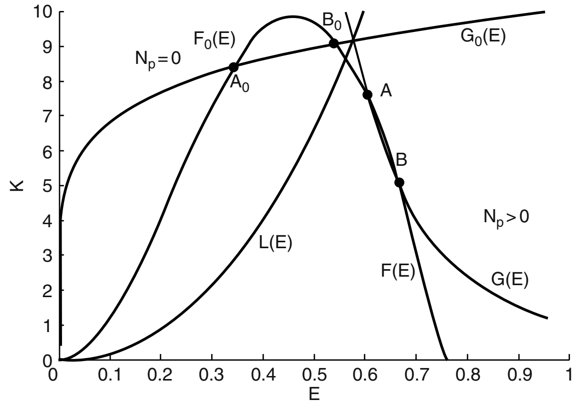

Fig. 1 Four fixed points: A_0 and B_0 with $N_p = 0$, A and B with $N_p > 0$. The parameters' values are: $\alpha = 2$, $\beta = 1$, $\gamma = 0.4$, $\delta = 0.1$, $\epsilon = 0.1$, $\eta = 0.1$, $a = 1$, $r = 0.1$, $\overline{E} = 0.96$, $\overline{N} = 1$

We can also investigate whether the existence of fixed points with $N_P = 0$ is compatible with the existence of fixed points with $N_P > 0$. The following proposition identifies necessary and sufficient conditions for the simultaneous existence of four fixed points A, B, A_0 and B_0.

Proposition 5. *Four fixed points exist -A_0 and B_0 with $N_P = 0$, A and B with $N_P > 0$- if and only if $\overline{N}_0 > \overline{N} > \overline{N}_1$, $max\{\overline{E}_0, \overline{E}_1\} < \overline{E} < \overline{E}_2$ and $\Omega > 0$.*

The proof of this proposition follows from Propositions 1 and 3.

For a numerical example in which four fixed point exist, see Fig. 1. When two saddle-point stable stationary states exist, the choice between B and B_0 depends on the initial conditions. This is a typical example of path dependence: the initial value of E and K determines the fixed point (B or B_0) that the growth trajectory will approach.

4.3 Welfare

The following proposition helps to identify the most significant variables that represent the dynamics of the economy.

Proposition 6. *The stationary state value of consumption c_R^* of the Rich is positively proportional to the stationary state value of physical capital K^*. More precisely, $c_R^* = \dfrac{r(\gamma+\delta)}{\gamma}K^*$ holds. The stationary state values of consumption c_S^* of the Poor working in the capitalistic sector and of consumption c_P^* of the Poor working in the traditional sector are positively proportional to the stationary state value of natural capital E^*. More precisely, $c_S^* = \dfrac{\alpha}{a}E^*$ and $c_P^* = \alpha E^*$ hold.*

This implies that the Rich are able to face effectively environmental degradation through physical capital accumulation. It means that exogenous changes leading to an increase in K^* ensure a growing c_R^*, even if E^* declines. This is not the case for the Poor, whose welfare is positively proportional to E^*.

The above proposition allows to focus on fixed point values of N_P, E and K. From these variables, Poor and Rich agents' welfare can be computed. The following proposition concerns Poor agents' welfare in the context in which two saddle-point stable stationary states coexist, B and B_0.

Proposition 7. *When two saddle-point stable stationary states coexist, B and B_0, then the value of E^* (and consequently P-agents' welfare) is higher in B than in B_0; the value of K^* (and consequently R-agents' welfare) may be higher or lower.*

The proof of such proposition is straightforward. The numerical simulations in Figs. 2–5 show how the fixed point values of K and E change, varying the parameters $\overline{E}$ and γ. In these figures, the continuous (dotted) lines indicate values of E^* and K^* corresponding to saddle-point stable stationary states (respectively, to fixed points with at least two eigenvalues with positive real part). Note that for some values of η and $\overline{E}$, the conditions set in Proposition 5 are satisfied: four fixed points exist and the initial levels of E and K determine whether B or B_0 will be reached. Moreover, as $\overline{E}$ (η) overcomes a minimum (maximum) level, only B_0-type fixed points with full specialization can be approached. Thus, point B_0 can be generated as a final step of an "excessive" depletion of the stock of environmental resources.

Notice that in the numerical examples in Figs. 2–5 when B and B_0 coexist, then P-agents' welfare is higher in B than in B_0 while the opposite holds for R-agents' welfare. Furthermore, observe that varying the parameters $\overline{E}$ and η, Poor agents'

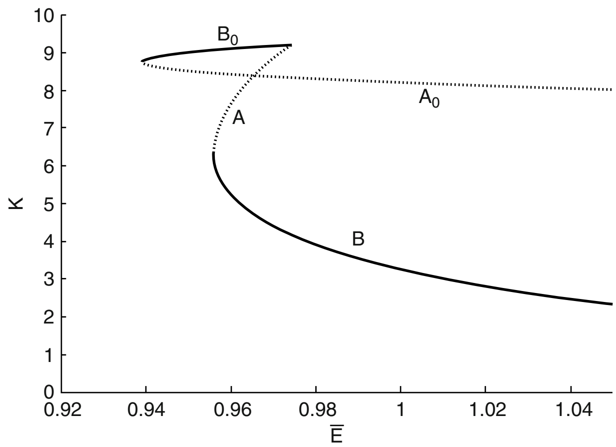

Fig. 2 The value of K, evaluated at the fixed points with $N_p > 0$ and $N_p = 0$ varying $\overline{E}$. *Continuous lines* represent saddle-point stable stationary states

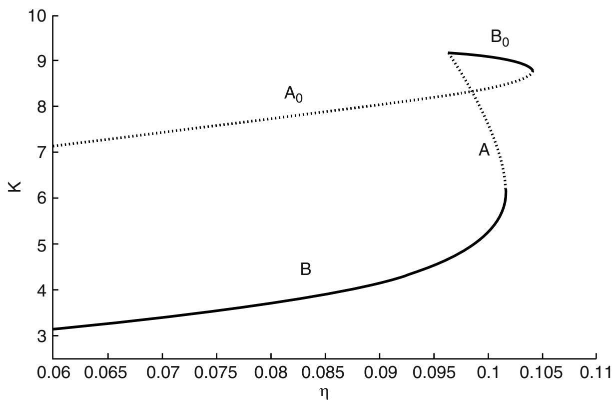

Fig. 3 The value of K, evaluated at the fixed points with $N_p > 0$ and $N_p = 0$ varying η. *Continuous lines* represent saddle-point stable stationary states

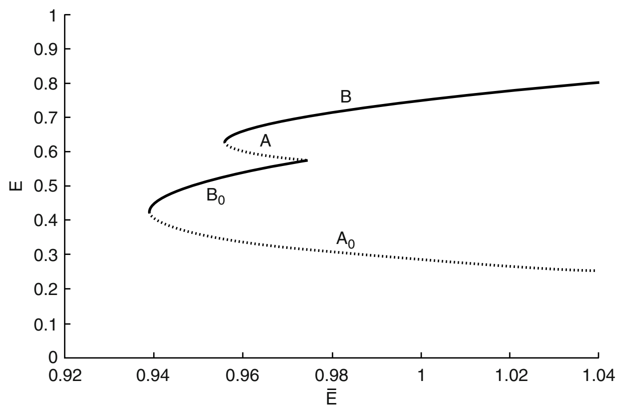

Fig. 4 The value of E, evaluated at the fixed points with $N_p > 0$ and $N_p = 0$ varying $\overline{E}$. *Continuous lines* represent saddle-point stable stationary states

welfare and Rich agents' welfare are inversely correlated, if evaluated at the fixed point without specialization B: a reduction of the endowment of the natural resource (or an increase of the negative impact of the modern sector on the environmental resource) leads to an increase of K^* and to a decrease of E^*. To the contrary, at the fixed point with specialization B_0, a positive correlation is observed. This difference is explained by the fact that along B a perverse structural change occurs in that the reduction of E^* generates a reduction of equilibrium wages associated to an increase of the proportion of Poor employed in the modern sector.

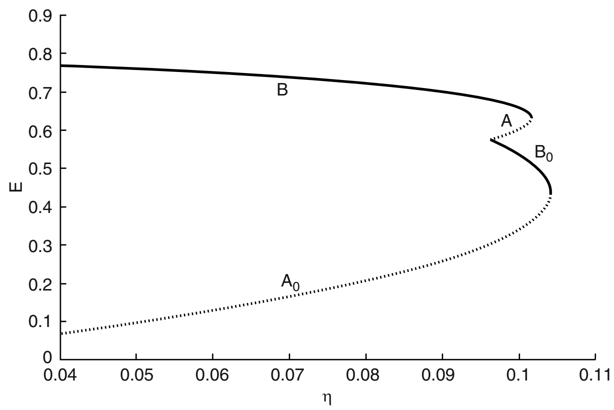

Fig. 5 The value of E, evaluated at the fixed points with $N_p > 0$ and $N_p = 0$ varying η. *Continuous lines* represent saddle-point stable stationary states

5 Discussion of the Results and Concluding Remarks

The bulk of growth models with environmental resources focuses on the relationship between environmental depletion and economic growth or total social welfare, while the links between environmental degradation, economic growth and asset distribution has often been overlooked. Indeed, vulnerability to scarcity or to reduction of natural capital is correlated to asset endowments: it depends on defensive substitution possibilities that, in turn, are affected by the availability of other production factors. Consequently environmental degradation can be expected to have a distributive impact too. This effect can be particularly relevant in developing countries where asset distribution is often highly skewed and the typology of income sources tend to differ across income levels. From this perspective, this article has attempted to apply a less aggregative approach to the study of the links between open access environmental resources, welfare of different population groups, composition and level of output.

The analysis of the model shows that, in contexts with highly concentrated physical capital distribution and free-access renewable natural resources, when physical-capital-intensive activities (i.e. the modern sector in our model) are relatively more polluting or resource demanding than the traditional activities, unexpected results can emerge. A labor shift to these activities can be fuelled not only by advantages in terms of total factor and labor productivity, but also by environmental degradation which, eventually, can lead to a complete specialization in the capital-intensive sector which drives the economy towards B_0, the unique stationary point that is admissible. If the environmental impact produced by these activities is still relatively high but does not overcome a certain threshold, two saddle-point stable stationary states exist: one with specialization in modern sector production (B_0) and one with the presence of both sectors (B). In this case the economic dynamics are path dependent and the selection between these fixed points is affected by the initial level of natural and physical capital. Economies with low natural capital endowments will be more likely to approach the fixed point B_0 and to follow a transition to a complete specialization. It is worth noting that, in such context, the poor obtain a higher welfare level in the stationary state without complete specialization than in the case of a complete process of "proletarianization". Therefore, our model shows that a trade-off between the welfare of the poor and the expansion of modern activities can emerge when environmental externalities and agents' heterogeneity are considered in a joint framework. Conversely, expansion of the modern activities might stimulate counter-intuitive consequences: an immiserizing growth process, namely, an output growth resulting in a further impoverishment of the poor and in a worsening of income distribution. In conclusion, our model suggests that in some contexts[6] the expansion of activities usually regarded as the engine of economic growth and, consequently, necessary (though not sufficient) conditions for poverty reduction, might actually increase poverty and inequality through the erosion of the resources upon which poor people depend.[7]

This trade-off does not emerge in the regime DTS, i.e. when the modern sector produces a relatively lower environmental impact than the traditional sector. In this scenario, for both the poor and the rich the welfare effect of an increase in output production and labor employment of the modern sector is positive.

In conclusion the proposed model shows that environmental degradation may represent a push factor of economic development in an economy polarized into two main classes (the rich and the poor) and characterized by the following stylized facts:

(a) The main income source of the rural poor is self-employment in traditional activities highly dependent on natural resources.
(b) Labour remuneration in rural sector represents the basic opportunity cost for (unskilled) labour in the economy. Thus, given that environmental degradation reduces labour productivity of the rural poor, it may depress wages.
(c) Production of the modern sector managed by the rich is less affected by the depletion of natural resources; they are able to defend themselves by partially substituting natural resources with physical capital accumulation and wage labour employment.

In this context, if the modern sector is sufficiently low-dependent on natural capital (i.e. the natural capital elasticity of the modern sector output is sufficiently low)

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[6] When income and asset concentration is high and the capitalistic sector is heavily polluting.

[7] Models that predict scenarios with undesirable economic processes are not new in literature. Actually, Antoci and Bartolini (1999, 2004), Antoci et al. (2005, 2008) and Antoci (2009) have proposed models in which negative externalities may constitute an engine of economic growth. In their models, economic growth produces negative externalities that reduce the capacity of natural or social environment to provide free goods. Agents try to defend themselves from welfare losses by increasing their labor supply in order to raise their consumption of private goods that are substitute for free access goods. This, in turn, stimulates economic growth. As a result, defensive strategies generate a growth path along which the production and consumption of private goods are higher than the socially optimal level.

environmental depletion may benefit the modern sector through an increase in low cost labour supply and, in turn, may stimulate physical capital accumulation and expansion of the modern sector. However, if the environmental impact of the modern sector is sufficiently heavy and relatively higher than that of the traditional sector, the structural change is likely to result in an increase in inequality.

Appendix

Proof Proposition 2

Substituting $N_P = \overline{N} - MK^{\frac{\gamma}{\gamma+\delta}} E^{\frac{\delta-1}{\gamma+\delta}}$, the system (10)–(12) becomes

$$\dot{K} = \beta(\gamma+\delta)M^{1-\gamma-\delta}K^{\frac{\gamma}{\gamma+\delta}}E^{\frac{2\delta+\gamma-1}{\gamma+\delta}} - \frac{1}{\lambda},$$

$$\dot{E} = E(\overline{E} - E) + M(\epsilon\alpha - \eta\beta M^{-\gamma-\delta})K^{\frac{\gamma}{\gamma+\delta}}E^{\frac{\delta-1}{\gamma+\delta}} - \epsilon\alpha\overline{N},$$

$$\dot{\lambda} = \lambda\left(r - \beta\gamma M^{1-\gamma-\delta}K^{-\frac{\delta}{\gamma+\delta}}E^{\frac{2\delta+\gamma-1}{\gamma+\delta}}\right),$$

where $M = \left(\frac{a\beta(1-\gamma-\delta)}{\alpha}\right)^{\frac{1}{\gamma+\delta}}$. Let (K^*, E^*, λ^*) denote the fixed point values of (K, E, λ). Remember that the fixed points without specialization are given by the intersections between the graphs of the functions $K = F(E)$ and $K = G(E)$ occurring below the curve $K = L(E)$ in the plane (E, K). Figure 6 shows all possible configurations of curves $K = F(E)$ and $K = G(E)$; in this figure, the curve $K = L(E)$ is drawn only if $K = F(E)$ and $K = G(E)$ have intersections above it; $E_1 := \frac{1-\delta}{1+\gamma}(\overline{E} - \epsilon\alpha\overline{N})$ indicates the value of E maximizing $F(E)$.

The Jacobian matrix evaluated at the fixed point (K^*, E^*, λ^*) is

$$J^* = \begin{pmatrix} h_K & h_E & h_\lambda \\ f_K & f_E & f_\lambda \\ g_K & g_E & g_\lambda \end{pmatrix}$$

with

$h_K = r > 0,$

$h_E = \frac{r\rho K^*}{\gamma E^*},$

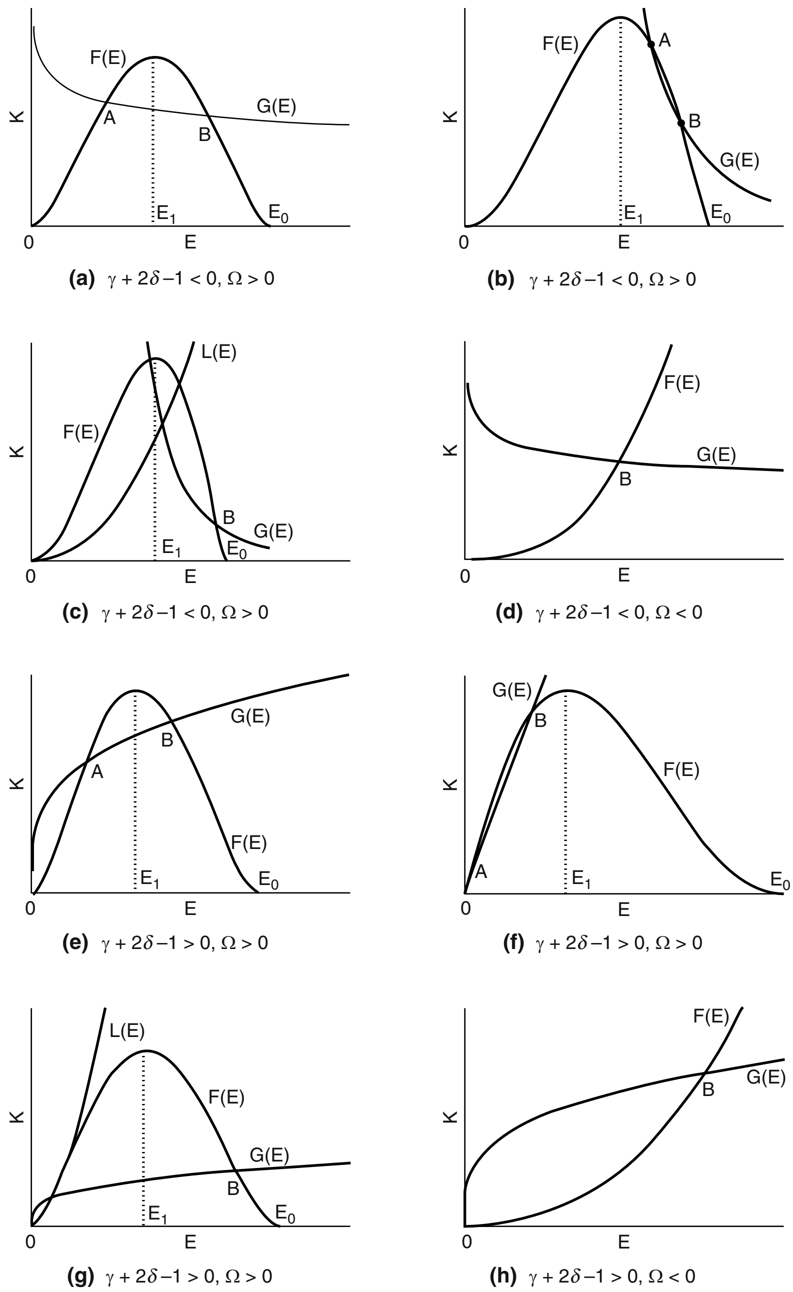

Fig. 6 Fixed points with $N_p > 0$

$$h_\lambda = \frac{1}{(\lambda^*)^2} = \left(\frac{r(\gamma+\delta)K^*}{\gamma}\right)^2 > 0,$$

$$f_K = -\frac{\gamma}{\gamma+\delta}\frac{\Omega E^*(\overline{N}-N_P)}{K^*},$$

$$f_E = \frac{1+\gamma}{\gamma+\delta}(E_1 - E^*),$$

$$f_\lambda = 0,$$

$$g_K = \frac{\gamma\delta}{(\gamma+\delta)^2(K^*)^2} > 0,$$

$$g_E = -\frac{\gamma}{(\gamma+\delta)^2}\frac{\rho}{E^*K^*},$$

$$g_\lambda = 0,$$

where $\rho = \gamma + 2\delta - 1$ and $\Omega = \alpha\left(\frac{\eta}{a(1-\gamma-\delta)} - \epsilon\right)$.

Notice that $sign(h_E)$=$sign(\rho)$, $sign(g_E)$=$sign(-\rho)$, $sign(f_E)$=$sign(E_1 - E^*)$ and $sign(f_K)$=$sign(-\Omega)$.

In order to study the stability properties of fixed points, we apply the methodology proposed by Wirl (1997). The eigenvalues of the system are the roots of the following characteristic polynomial

$$P(z) = z^3 - tr(J^*)z^2 + wz - |J^*|,$$

where

$$tr(J^*) = h_K + f_E + g_\lambda, \qquad |J^*| = h_\lambda(f_K g_E - f_E g_K),$$
$$w = -h_\lambda g_K + h_K f_E - h_E f_K.$$

The following results can be easily proved.

Lemma 1. *If $E^* < E_1$, then $tr(J^*) > 0$.*

Lemma 2. *If $\Omega > 0$, then $|J^*| < 0$ in A and $|J^*| > 0$ in B.*
If $\Omega < 0$, then $|J^*| > 0$ in the unique admissible fixed point.

Lemma 3. *If $\rho < 0$, then $w < 0$.*
If $\rho > 0$ and $\Omega < 0$, then $w < 0$.
If $\rho > 0$ and $\Omega > 0$, then $E^* > \frac{1}{2}\left(\overline{E} - \epsilon\alpha\overline{N} - \frac{r\delta}{\gamma}\right)$ is a sufficient condition for $w < 0$.

It is now possible to discuss the stability properties of A and B, in the regime $\Omega > 0$, and of the unique admissible fixed point in the regime $\Omega < 0$. As explained in the main text, a fixed point (K^*, E^*, λ^*) is said "saddle-point stable" if J^* admits two eigenvalues with negative real parts.

Stability Analysis of A

By Lemma 2, $|J^*| < 0$ holds in A; therefore, A is either a saddle with two positive eigenvalues or a sink. Conditions for local attractivity are (see Wirl, 1997): $tr(J*) < 0$, $|J^*| < 0$ and $w > 0$. Figure 6 shows that A may assume two possible configurations. In the cases (a) and (b), $\rho < 0$ holds; thus, from Lemma 3, it follows that $w < 0$, therefore A is not attractive. In the cases (e) and (f), $E^* < E_1$ holds in A; this implies, by Lemma 1, that $tr(J*) > 0$. Thus A cannot be attractive. In short, the fixed point A is always a saddle with two positive eigenvalues.

Stability Analysis of B and of the Unique Fixed Point in the Regime $\Omega < 0$

In B and in the unique fixed point in the regime $\Omega < 0$, $|J^*| > 0$ holds; therefore, such a fixed point is either a source or a saddle point with a two-dimensional stable manifold (Wirl 1997). Wirl finds that a positive determinant and a negative coefficient w are sufficient conditions for saddle-point stability. Given Lemmas 2 and 3, this happens when $\rho < 0$ (Fig. 6, cases a–d) or when $\rho > 0$ and $\Omega < 0$ (Fig. 6, case h). If $\rho > 0$ and $\Omega > 0$, the sign of w is not univocally determined. Consequently, in this case, B may be repulsive or saddle-point stable. However, by Lemma 3, $E^* > \frac{1}{2}\left(\overline{E} - \epsilon\alpha\overline{N} - \frac{r\delta}{\gamma}\right)$ is a sufficient condition for saddle-point stability (Fig. 6, cases e–g); this completes the proof of Proposition 2.

Proof of Proposition 4

In the regime $N_P = 0$, the dynamic system (10)–(12) becomes

$$\dot{K} = \beta(\gamma + \delta)K^{\gamma} E^{\delta} \overline{N}^{1-\gamma-\delta} - \frac{1}{\lambda},$$
$$\dot{E} = E(\overline{E} - E) - \beta\eta K^{\gamma} E^{\delta} \overline{N}^{1-\gamma-\delta},$$
$$\dot{\lambda} = \lambda(r - \beta\gamma K^{\gamma-1} E^{\delta} \overline{N}^{1-\gamma-\delta}).$$

In order to study the stability properties of fixed points, we calculate the Jacobian matrix J_0^* evaluated at a fixed point (K^*, E^*, λ^*) with $N_P = 0$

$$J_0^* = \begin{pmatrix} h_{0K} & h_{0E} & h_{0\lambda} \\ f_{0K} & f_{0E} & f_{0\lambda} \\ g_{0K} & g_{0E} & g_{0\lambda} \end{pmatrix}$$

with

$h_{0K} = r(\gamma + \delta) > 0,$

$h_{0E} = \dfrac{r\delta(\gamma + \delta)K^*}{\gamma E^*} > 0,$

$h_{0\lambda} = \dfrac{r^2(\gamma + \delta)^2(K^*)^2}{\gamma^2} > 0,$

$f_{0K} = -r\eta < 0,$

$f_{0E} = \overline{E}(1 - \delta) - (2 - \delta)E^*,$

$f_{0\lambda} = 0,$

$g_{0K} = \dfrac{\gamma(1 - \gamma)}{(\gamma + \delta)(K^*)^2} > 0,$

$g_{0E} = -\dfrac{\gamma\delta}{(\gamma + \delta)K^* E^*} < 0,$

$g_{0\lambda} = 0.$

The eigenvalues of the system are the roots of the following characteristic polynomial

$$P(z) = z^3 - tr(J_0^*)z^2 + wz - |J_0^*|,$$

where

$$tr(J_0^*) = h_{0K} + f_{0E}, \qquad |J_0^*| = h_{0K}(f_{0K}g_{0E} - f_{0E}g_{0K}),$$
$$w = -h_{0\lambda}g_{0K} + h_{0K}f_{0E}f_{0K}.$$

Let us first consider $tr(J_0^*)$. Figure 7 shows all possible configurations of the fixed points with $N_P = 0$. The fixed points correspond to the intersections between the graphs of the functions $K = F_0(E)$ and $K = G_0(E)$, occurring above the curve $K = L(E)$ in the plane (E, K).[8] Notice that $f_{0E} > 0$ if $E^* < E_M := \dfrac{\overline{E}(1 - \delta)}{2 - \delta}$, where E_M is the value of E maximizing $F_0(E)$. Being $E^* < E_M$ in A_0, $f_{0E} > 0$ and $tr(J_0^*) > 0$ hold in A_0 (see cases a-c in Fig. 7).

In Fig. 7a, $E^* < E_M$ holds in B_0; therefore $f_{0E} > 0$ and $tr(J_0^*) > 0$. In Fig. 7b, $E^* > E_M$ holds in B_0; therefore $f_{0E} < 0$ and the sign of $tr(J_0^*)$ is not univocally determined.

[8] In Fig. 7, the curve $K = L(E)$ is not drawn when no intersection between $K = F_0(E)$ and $K = G_0(E)$ occurs below it.

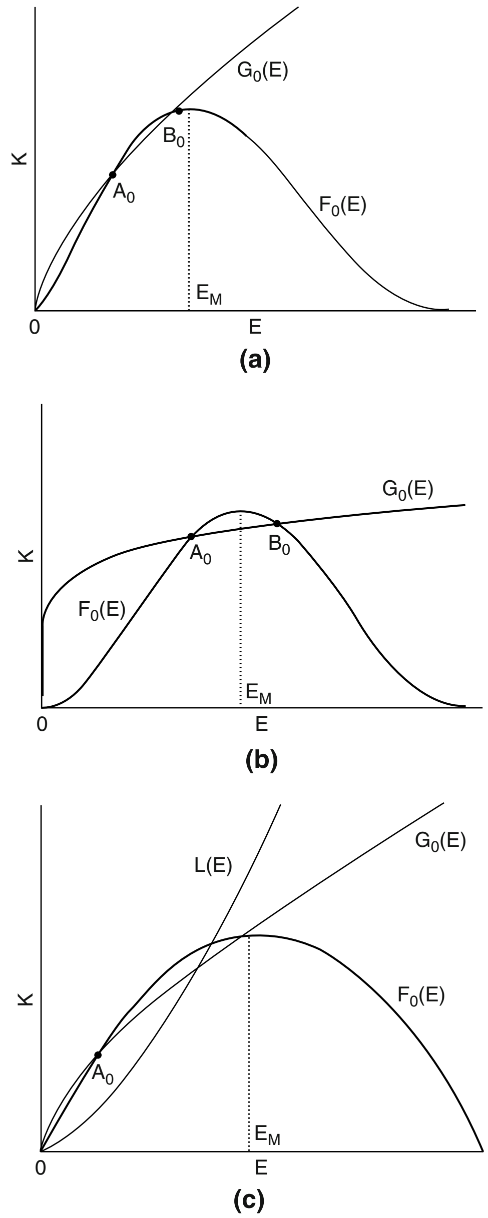

Fig. 7 Fixed points with $N_p = 0$

Let us now analyze the sign of $|J_0^*|$. We can observe that $F_0' > G_0'$ in A_0, while $F_0' < G_0'$ in B_0, where $F_0' = -\dfrac{f_{0E}}{g_{0K}}$ and $G_0' = -\dfrac{g_{0E}}{g_{0K}}$. It follows that $|J_0^*| < 0$ in A_0 while $|J_0^*| > 0$ in B_0.

Finally, let us consider

$$w = -\frac{r^2(\gamma+\delta)}{\gamma(1-\gamma)} + r(\gamma+\delta)(\overline{E}(1-\delta) - (2-\delta)E^*) + \frac{\delta\eta r^2(\gamma+\delta)K^*}{\gamma E^*}.$$

Replacing[9]

$$K^* = \frac{\gamma E^*(\overline{E} - E^*)}{r\eta} \tag{13}$$

we obtain

$$w = r(\gamma+\delta)\left\{-\frac{r}{\gamma(1-\gamma)} + \overline{E} - 2E^*\right\} < 0$$

if $E^* > \dfrac{1}{2}\left(\overline{E} - \dfrac{r}{\gamma(1-\gamma)}\right)$.

Stability Analysis of A_0

$|J_0^*| < 0$ holds in A_0; therefore A_0 may be a saddle point with two eigenvalues with positive real parts or a sink. Given that $tr(J_0^*) > 0$, local attractivity is excluded.

Stability Analysis of B_0

In B_0 we have $|J_0^*| > 0$; therefore B_0 is either a source or a saddle-point stable stationary state. If $E^* > \dfrac{1}{2}\left(\overline{E} - \dfrac{r}{\gamma(1-\gamma)}\right)$, then $w < 0$ and consequently the fixed point cannot be repulsive (see Wirl, 1997). That is, $E^* > \dfrac{1}{2}\left(\overline{E} - \dfrac{r}{\gamma(1-\gamma)}\right)$ is a sufficient condition for saddle-point stability.

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[9] Formula (13) is obtained from equations $\dot{E} = 0$ and $\dot{\lambda} = 0$.

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