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REGULAR ARTICLE

Environmental degradation, self-protection choices and coordination failures in a North–South evolutionary model

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Abstract Environmental degradation may lead agents to increase their work effort to replace the consumption of depleted free access environmental goods with that of private substitute goods. The rise in the activity level that follows may further deplete the environment, which in turn increases the production and consumption of substitute goods. Using a North–South evolutionary model, we show that the existence of a coordination failure among interacting heterogeneous agents may lead the economy towards Pareto-dominated attracting stationary states where individuals work and produce "too much" (i.e. more than socially optimal). Finally, we analyse possible welfare effects of transferring the environmental impact of Northern production to the South and show that such a policy may decrease welfare in both hemispheres.

JEL Classification C70 · D62 · O13 · O40 · Q20

1 Introduction

The present paper examines the relationship between environmental self-protection choices and economic growth in the context of a North-South model. By environmental self-protection choices we mean choices that agents can do to protect themselves

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against the deterioration of the environment they live in.[1] The argument is well-known in environmental literature: many natural resources that were still freely available in developed economies some decades ago (e.g. meadows, woods, unpolluted air and water etc…) may deteriorate or become scarce as income grows. To counterbalance such a trend, people tend to replace consumption of these "free" environmental public goods with that of expensive private goods that may alleviate the damage deriving from environmental degradation.

Everyday life provides many examples of environmental self-protection expenditures such as: mineral water (to protect against tap water pollution), double glazing (to protect against traffic noise), small masks (that pedestrians wear to protect against the air pollutants released by motor vehicles) or health expenditures against pollution-related diseases (e.g. asthma and skin diseases).[2] These are just a few textbook examples of self-protection choices caused by environmental degradation that have been rapidly increasing in many countries in the last decades. However, it is also possible to identify a further, very large set of expenditures that are not exclusively in response to environmental degradation, but derive in part from it. An example could be spending on a package holiday in some tropical paradise. In this case, the curiosity of visiting unknown places undoubtedly plays an important part in the choice of this destination, but it is also likely to be influenced by the degradation of the sea close to home, particularly in the vicinity of big urban centres. It is therefore reasonable to expect that the incentive to go on this holiday will be greater the lower the quality of the sea near home. Even the purchase of an entrance ticket for the swimming pool or the construction of a pool in one's back garden could be a response to needs other than environmental ones (such as having access to a prestigious sport club or constructing a luxury good that indicates one's social status), but it can also partly be interpreted as defensive environmental expenditure, motivated by the desire to swim in clean waters rather than in a polluted sea. A similar argument can be made for buying a boat, which can be used for moving from a no-swimming beach to one less affected by environmental degradation.

Both ecological and economic motivations, moreover, can affect the choice of individuals to move away from a degraded urban centre—a transfer that is generally induced for both financial reasons (finding housing at a lower cost) and ecological and social reasons (bothersome traffic and urban pollution, and the desire for more living space which can be satisfied by buying a more spacious home, possibly with a garden). Over the years, this phenomenon has caused towns to expand outwards, encouraged also by technological progress which has brought basic services, once enjoyed only in towns, out to the countryside. This has led to increasing urban sprawl. Paradoxically, the increasing extension of this process is bringing about a series of undesirable effects for individuals which sometimes worsen precisely the problems

[1] See, for instance, Hueting (1980), Leipert (1989a,b) Leipert and Simonis (1989), United Nations (1993, 2003) and Garrod and Willis (1999) for alternative classifications of environmental defensive expenditures generated by these self-protection choices. See Escofet and Bravo-Peña (2007) for an interesting case study.

[2] Several epidemiological studies (e.g. Friedman et al. 2001; Kunzli et al. 2000; Pope et al. 2002) confirm the existence of a strong correlation between urban concentration of air pollutants (ozone and PM10) and acute respiratory diseases in different countries.

that caused them to leave the town in the first place, such as a reduction of green and public areas or the increase in traffic jams with the resultant increase of pollution and of the time necessary to travel to work.

Even the migration flows across different countries or regions can partially respond to ecological needs and thus be interpreted as self-protection choices. Although most migration flows are motivated by economic reasons (such as the desire to find a better job and better living conditions), many flows can be directly attributed to environmental degradation and ecological catastrophes that create the need to escape from the country of origin. This ecological motivation has gradually become so important that a specific term, i.e. the "environmental refugee" (Myers 1997; Bates 2002), has been coined in the literature to identify these migrants. Many environmental refugees are likely to come from developing countries where most of the population cannot afford to protect from environmental degradation and is therefore more vulnerable to ecological problems (such as the loss of the land's fertility due to its pollution and overexploitation that compels poor farmers to leave their sites). Deep ecological problems, however, can hit both developed and developing countries, therefore these migration flows are partially independent of the income level in the country of origin. For instance, the rise in the sea level deriving from global warming in the long run might flood coastal lowlands in both developing countries (e.g. Bangladesh or the Maldives), and in developed countries (e.g. Netherlands or New York city; see Yin et al. 2009).

Many of the expenditures of inhabitants of big cities are at least partially conditioned by defensive reasoning (cf. for example Hueting 1980; Antoci et al. 2008; Antoci 2009). Consider the choice of using a car as a means of transport. This choice can partially be caused by air pollution: individuals who would have preferred to go by bicycle are forced to use their car because the air is unbreathable. Air pollution thus reinforces and further increases the decision to use private cars which raises in turn air pollution. The shortage of parks and areas for children to play without the constant supervision of adults imposes further defensive expenditures. The massive use of home entertainment by children is partly a result precisely of the lack of such areas, the degradation of the urban environment and the need to protect children from the dangers of urban traffic. The scarcity of green space can further induce individuals to pay for an entrance ticket for a protected natural area or to spend money on a day out to enjoy nature and leisure activities. Another possible expenditure may be joining a gym, substituting physical activity in a park in the open air with exercise carried out in a sports centre.

The notion of defensive expenditures has received much attention in the environmental literature where there is a large debate on how GDP should be corrected as a welfare measure to account for defensive expenditures since the latter may increase GDP without augmenting the agents' well-being (cf. Aronsson et al. 1999; Kadekodi and Agarwal 2000; Vincent 2000; Cairns 2004). A few empirical studies have also tried to quantify the dimension of such expenditures as a share of GDP. Given the difficulty to define the categories of defensive expenditures in operational terms, results are very sensitive to the classification being adopted and tend to differ according to the kind of defensive expenditure taken into account. In the literature, however, there exists wide agreement on the fact that defensive expenditures are a relevant share of GDP and have been growing steadily over time. In his seminal contribution on this issue, Leipert (1989a) estimate that in West Germany the environmental defensive expenditures increased from 1.5% of GDP in 1970 to 3.4% in 1988. When enlarging the notion of defensive expenditures to account also for the additional costs (in terms of transports, housing, security, health and work) incurred by households and firms to protect from environmental and social degradation, Leipert (1989b, p 851) finds that "the ratio of defensive costs increased from 5.6% to 10.0% during the period under review". Other studies have subsequently tried to perform similar estimations, focusing attention mainly on different subsets of the environmental defensive expenditures. In the case of Italy, for instance, Cullino (1993) finds that over the period 1986-'88 such expenditures increased both in absolute terms and as a share of the Italian GDP, up to 1.58%; a result in line with the one reported by Statistics Canada (1998) that estimates environmental defensive expenditures to be equal on average to 1.6% of the overall GDP of the European Union, with shares above 2% for single countries. Limiting their analysis to the resource spent or production possibilities foregone because of water pollution in the industrial city of Chongqing (in the Sichuan basin of China), Yongguan et al. (2001) find that the resource costs of water pollution range between 1.2% and 4.3% of GDP according to the estimation approach being adopted. In another study on China that focuses mainly on the aggregate costs of air pollution in the country, the World Bank (1997) finds that the correspondent damages are about 8% of the Chinese GDP. It should be beard in mind, however, that all these calculations are to be interpreted as lower bound values since they do not take into account many categories of defensive expenditures and the non-monetary costs of environmental degradation (e.g. loss of ecological functions and of life quality due to environmental degradation). Moreover, in the absence of more recent studies on this issue, one can reasonably expect that the environmental defensive expenditures have become even higher in the last few years due to stricter environmental standards in most countries and consequently higher environmental protection investments by firms and governments.

The research line pursued (and further extended) in this paper intends to go one step forward with respect to the traditional literature, showing that environmental defensive expenditures may contribute not only to an increase in the output level, but also to a self-enforcing growth process.

In particular, self-protective consumption may give rise to a vicious circle between environmental degradation and an increase in private consumption with undesirable effects for the economic system at the aggregate level. Environmental deterioration, in fact, may induce agents to work harder to substitute previously free environmental goods with produced substitute goods. The production of substitute goods may further deplete the environment, which in turn increases the production and consumption of substitute goods. Thus, the mechanism of substitution of depleted natural resources with private goods may contribute to a self-nourishing growth process: economic growth increases environmental degradation which, in turn, generates further growth. The idea that environmental negative externalities may promote economic growth was first introduced by Antoci and Bartolini (1999, 2004) in an evolutionary game context in which the authors show that agents' welfare may decrease as the aggregate output of private goods increases.[3] Similar results can be obtained using neoclassical growth models in which the agents are assumed to have perfect foresight (cf. Bartolini and Bonatti 2002, 2003; Antoci et al. 2005, 2007). This shows that the possibility of an "undesirable" (i.e. Pareto-dominated) growth process does not depend on the hypothesis of bounded rationality underlying the evolutionary game model but rather on the existence of coordination failures among the agents.

Differently from previous contributions in this line of research, the present work extends the analysis from a single-population to a North-South evolutionary context. Our objective is to analyse possible undesirable feedback effects due to the interaction between heterogeneous agents' consumption choices in the two hemispheres. Agents differ in two main respects: for the strategy they choose (whether to self-protect or not) and for the hemisphere they belong to (North or South). In particular, agents belonging to different hemispheres may differ with respect to their self-protection capability (Northern agents having on average a higher self-protection potential than Southern agents), the endowment of environmental goods at disposal and the stringency of the ecological regulations adopted in their own hemisphere. Beyond the analysis of potential feedback effects between the two hemispheres, the North-South context examined in this paper allows also for more complex dynamics with respect to the previous literature, that may emerge in a two-dimensional space from the interaction between heterogeneous populations.

The paper has the following structure. Section 2 introduces the model. Sections 3 and 4 provide the basic relevant mathematical results. Section 5 deals with the welfare analysis. Section 6 examines the welfare effects of transferring the environmental impact of Northern production to the South. Finally, Sect. 7 summarizes the main findings of the paper.

2 The model

There are two hemispheres: North (N) and South (S). There are two populations of economic agents: the population of the North (N-agents) and the population of the South (S-agents).

Time is continuous. At every moment of time t, j-agents' welfare ($j = N, S$) depends on three goods: leisure, a free access flow $E^j(t)$ of a renewable natural resource, and a flow of a non-storable private good $Y^j(t)$. The natural resource is depleted by the production process of the private good.

The private good is produced by labor alone. Let us indicate with $L^j(t)$ the j-agents' labor supply.

At each moment of time, every agent in hemisphere j is endowed with one unit of time that can be used for work or leisure and can decide whether to work little, $L^j(t) = \overline{L}_l^j$, or hard, $L^j(t) = \overline{L}_h^j$; $\overline{L}_l^j$ and $\overline{L}_h^j$ are parameters of the model satisfying the condition: $0 < \overline{L}_l^j < \overline{L}_h^j < 1$. If a j-agent works little, he/she produces and

[3] Some other theoretical contributions (see e.g. Shogren and Crocker 1991) also take environmental defensive expenditures explicitly into account, but they overlook their possible implications on economic growth.

consumes the fixed amount $Y^j(t) = \bar{Y}_1^j$ of the non-storable consumption good. In general, we can think of $\bar{Y}_1^j$ as a subsistence consumption level. If a j-agent works hard, he/she produces and consumes $Y^j(t) = \bar{Y}_1^j + \bar{Y}_2^j$. In other words, if the agent works $\overline{L}_h^j$, he/she produces and consumes an additional fixed amount $\bar{Y}_2^j$ of the good that can be used as a substitute for the depleted environmental resource. Only the agents that work hard can thus afford substitution consumption.[4] The output Y of the non-storable private good can thus be interpreted as a binary variable that can have only two strictly positive values: either $\bar{Y}_1^j$ or $\bar{Y}_1^j + \bar{Y}_2^j$.[5]

Let us indicate with $x(t) \in [0, 1]$ the share of agents that choose to work hard in the North at the moment of time t (consequently, $1 - x(t)$ is the share of agents that choose to work little). The total amount produced and consumed in the North at the moment of time t will then be given by:[6]

$$Y^N(x) := \left(\bar{Y}_1^N + \bar{Y}_2^N\right) x + \bar{Y}_1^N (1 - x) = \bar{Y}_1^N + \bar{Y}_2^N x \tag{1}$$

Similarly, we indicate with $z(t) \in [0, 1]$ the share of agents that choose to work hard in the South at the moment of time t. The aggregate production and consumption in the South is then equal to:

$$Y^S(z) := \left(\bar{Y}_1^S + \bar{Y}_2^S\right) z + \bar{Y}_1^S (1 - z) = \bar{Y}_1^S + \bar{Y}_2^S z \tag{2}$$

Let us indicate with the parameter $\overline{E}^N > 0$ the value of the flow of the common access natural resource in the North when no production takes place ($\overline{E}^N$ can be interpreted as the endowment of the natural resource in the North). This amount is reduced by the pollution caused by the production and consumption of private goods in both hemispheres. Let us indicate with E^N the flow of the environmental resource net of the reduction due to economic activity. We assume that the natural resource regenerates instantaneously (i.e. the reduction of $\overline{E}^N$ at any moment of time t does not carry over into successive periods);[7] consequently, E^N is a function of x and z only. More specifically, we assume:

$$E^N(x, z) := \overline{E}^N - \alpha Y^N(x) - \delta Y^S(z) \tag{3}$$

[4] The existence of a homogeneous produced good that satisfies both basic and environmental needs is assumed in the paper for analytical simplicity. Recalling the example above, however, one can think of two distinct goods, $\bar{Y}_1^j$ being the production of food that ensures agents' survival and $\bar{Y}_2^j$ the production of swimming pools that provide a substitute for the polluted sea.

[5] It follows that the fixed amounts $\bar{Y}_1^j$ and $\bar{Y}_2^j$ are parameters of the model.

[6] We set population size equal to 1 in both hemispheres. In what follows, moreover, we will omit the time variable t to simplify the notation.

[7] This simplifying assumption can be easily relaxed without altering (and actually reinforcing) the main results deriving from the model. See the concluding section for further discussion on this point.

where α and δ are strictly positive parameters representing the negative impacts due to aggregate outputs of the North and of the South, respectively.

Replacing $Y^N(x)$ and $Y^S(z)$ with Eqs. (1) and (2) and collecting terms, we obtain:

$$E^N(x, z) = A - \alpha \bar{Y}_2^N x - \delta \bar{Y}_2^S z \tag{4}$$

where $A := \overline{E}^N - \alpha \bar{Y}_1^N - \delta \bar{Y}_1^S$.

Mutatis mutandis, the same applies to the South:

$$E^S(x, z) := \overline{E}^S - \gamma Y^N(x) - \beta Y^S(z) \tag{5}$$

with $\overline{E}^S, \gamma, \beta > 0$.

Substituting (1) and (2) into (5), we get:

$$E^S(x, z) = B - \gamma \bar{Y}_2^N x - \beta \bar{Y}_2^S z \tag{6}$$

where $B := \overline{E}^S - \beta \bar{Y}_1^S - \gamma \bar{Y}_1^N$.

Notice that the parameters A and B can be interpreted, respectively, as the Northern and Southern environmental flows net of the negative impact due to subsistence activities (i.e. production and consumption of $\overline{Y}_1^j$) in both hemispheres. As Eqs. (4) and (6) show, these flows are further reduced by the defensive activities (i.e. production and consumption of $\overline{Y}_2^j$) in both hemispheres.

Finally, suppose that all agents have the same payoff function in both hemispheres. We assume that each agent has a logarithmic additively separable payoff function that depends on three arguments: (i) leisure, (ii) (subsistence) consumption of the produced good ($\overline{Y}_1^j$) and (iii) environmental consumption. The latter can be consumption of the free natural resource E and (substitution) consumption of the produced good ($\overline{Y}_2^j$). As mentioned above, if an agent works little he/she cannot afford such private consumption. Therefore, the payoff function of an agent who works little in hemisphere $j (j = N, S)$ will be:

$$P_l^j(x, z) = a \ln \left(1 - L_l^j\right) + b \ln \bar{Y}_1^j + \ln E^j(x, z) \tag{7}$$

where $a, b > 0$.

If an agent works hard in hemisphere j he/she can enjoy both the environmental good in j and the substitute good that he/she produces. The payoff function of an agent who works hard in the North will then be:

$$P_h^N(x, z) = a \ln \left(1 - L_h^N\right) + b \ln \bar{Y}_1^N + \ln \left[E^N(x, z) + d\bar{Y}_2^N\right] \tag{8}$$

while that of an agent who works hard in the South will be:

$$P_h^S(x,z) = a\ln(1-L_h^S) + b\ln\bar{Y}_1^S + \ln\left[E^S(x,z) + e\bar{Y}_2^S\right] \tag{9}$$

where $a, b, d, e > 0$.

Notice that in Eq. (9) $E^S(x,z)$ and $\bar{Y}_2^S$ are perfect substitutes for Southern agents that work hard, e measuring their marginal rate of substitution. Similarly, in Eq. (8), $E^N(x,z)$ and $\bar{Y}_2^N$ are perfect substitutes for Northern agents who work hard, d being the marginal rates of substitution between the two goods.

Subtracting (7) when $j = N$ from (8), we then obtain the payoff difference between working hard and working little in the North:

$$\Delta P^N(x,z) := P_h^N(x,z) - P_l^N(x,z) = a\ln\frac{1-L_h^N}{1-L_l^N} + \ln\frac{\left[E^N(x,z) + d\bar{Y}_2^N\right]}{E^N(x,z)}$$

Similarly, subtracting (7) when $j = S$ from (9), the payoff difference in the South is equal to:

$$\Delta P^S(x,z) := P_h^S(x,z) - P_l^S(x,z) = a\ln\frac{1-L_h^S}{1-L_l^S} + \ln\frac{\left[E^S(x,z) + e\bar{Y}_2^S\right]}{E^S(x,z)}$$

We assume that if the payoff difference is positive, the number of people that work hard will increase since working hard provides a higher payoff than working little. The opposite holds if the payoff difference is negative. Finally, if the payoff difference equals zero in hemisphere j people in that hemisphere are indifferent to working either hard or little, so that the population share that works hard (little) remains constant over time. Therefore, we can write:

$$\Delta P^N(x,z) \gtreqless 0 \Rightarrow \dot{x} \gtreqless 0 \quad \Delta P^S(x,z) \gtreqless 0 \Rightarrow \dot{z} \gtreqless 0 \tag{10}$$

where $\dot{x}$ and $\dot{z}$ are the time derivatives of x and z, respectively.

Replacing $E^N(x,z)$ with (4) and $E^S(x,z)$ with (6), we can rewrite the inequalities of condition (10) as follows:

$$d\bar{Y}_2^N + \left[\alpha\bar{Y}_2^N x + \delta\bar{Y}_2^S z - A\right](\overline{L}^N - 1) \gtreqless 0 \quad \Rightarrow \quad \dot{x} \gtreqless 0 \tag{11}$$

$$e\bar{Y}_2^S + \left(\beta\bar{Y}_2^S z + \gamma\bar{Y}_2^N x - B\right)(\overline{L}^S - 1) \gtreqless 0 \quad \Rightarrow \quad \dot{z}_t \gtreqless 0 \tag{12}$$

where

$$\overline{L}^N := \left(\frac{1-\overline{L}_l^N}{1-\overline{L}_h^N}\right)^a > 1, \quad \overline{L}^S := \left(\frac{1-\overline{L}_l^S}{1-\overline{L}_h^S}\right)^a > 1 \tag{13}$$

For the sake of simplicity, we assume that the dynamics of x and z are given by the so-called "replicator dynamics" (see e.g. Weibull 1995):

$$\begin{cases} \dot{x} = x(1-x)\Delta P^N(x,z) \\ \dot{z} = z(1-z)\Delta P^S(x,z) \end{cases} \tag{14}$$

Dynamics (14) describes an adaptive process based on an imitation mechanism: each period, part of the population changes its strategy, adopting the more remunerative one (working hard or little).

Replicator dynamics may be generated by several learning mechanisms and are typically introduced assuming random pairwise matching between economic agents (see Borgers and Sarin 1997; Schlag 1998). Differently from that context, we study here a *population game* in which the payoff of an individual adopting a given strategy at time t depends on the strategies that *all* individuals are choosing at the same moment in both hemispheres.[8]

3 Basic mathematical results

The dynamic system (14) is defined in the square Q:

$$Q = \{(x,z) : 0 \leq x \leq 1, 0 \leq z \leq 1\}.$$

In what follows we will denote with $Q_{x=0}$ the side of Q where $x = 0$, with $Q_{x=1}$ the side where $x = 1$. Similar interpretations apply to $Q_{z=0}$ and $Q_{z=1}$. All sides of this square are invariant; namely, if the pair (x,z) initially lies on one of the sides, then the whole correspondent trajectory also lies on that side.

Note that the states $\{(x,z) = (0,0), (0,1), (1,0), (1,1)\}$ are always fixed points of the dynamic system (14). In such states, only one strategy is played in each hemispere. Other fixed points are the points of intersection between the locus $\Delta P^S(x,z) = 0$ (where $\dot{z} = 0$) and the interior of the sides $Q_{x=0}$, $Q_{x=1}$ (where it holds $\dot{x} = 0$). In such fixed points, both available strategies are played in the South, while all agents choose the same strategy in the North. Mutatis mutandis, the same applies to the fixed points at the intersection between the locus $\Delta P^N(x,z) = 0$ (where $\dot{x} = 0$) and the interior of the sides $Q_{z=0}$, $Q_{z=1}$(where it holds $\dot{z} = 0$). In this case, both strategies are played in the North, whereas all Southern agents choose the same strategy. The remaining possible fixed points are those in the interior of Q where the loci $\Delta P^N(x,z) = 0$ and $\Delta P^S(x,z) = 0$ meet; in such states, all strategies coexist.

[8] See Sethi and Somanathan (1996) for an application of replicator equations in a context similar to ours.

From (11) and (12), we obtain that the loci $\dot{x} = 0$ and $\dot{z} = 0$ are respectively represented by the following equations:

$$z = \frac{1}{\delta \bar{Y}_2^S}\left(A - \frac{d\bar{Y}_2^N}{\overline{L}^N - 1}\right) - \frac{\alpha \bar{Y}_2^N}{\delta \bar{Y}_2^S} x \tag{15}$$

$$z = \frac{1}{\beta \bar{Y}_2^S}\left(B - \frac{e\bar{Y}_2^S}{\overline{L}^S - 1}\right) - \frac{\gamma \bar{Y}_2^N}{\beta \bar{Y}_2^S} x \tag{16}$$

where $\overline{L}^N > 1$ and $\overline{L}^S > 1$ (see (13)).

Notice that the slopes of (15) and of (16) are negative. Furthermore, the slope of (15) is greater than that of (16) if $\frac{\alpha}{\delta} < \frac{\gamma}{\beta}$. Finally, notice that $\Delta P^N(x, z) > 0$ (i.e. $\dot{x} > 0$) above (15) and that $\Delta P^S(x, z) > 0$ (i.e. $\dot{z} > 0$) above (16).

Proposition 1 *The Jacobian matrix of the system (14) evaluated at the fixed point* $(x, z) = (i, j), i = 0, 1$ *and* $j = 0, 1$*, is*:

$$\begin{bmatrix} (1-2i)\Delta P^N(i, j) & 0 \\ 0 & (1-2j)\Delta P^S(i, j) \end{bmatrix}$$

and has eigenvalues: $(1-2i)\Delta P^N(i, j)$ *and* $(1-2i)\Delta P^S(i, j)$.

From the analysis of the sign of such eigenvalues it is possible to derive the stability of the fixed points (0, 0), (0, 1), (1, 0), (1, 1).[9] In particular, one can associate to each fixed point two threshold values, one for the parameter A and the other for B, such that when the threshold values are crossed, the signs of the eigenvalues of the fixed point change and consequently its stability properties change.

Consider, for instance, the fixed point (0, 0). It is easy to show that the eigenvalue of (0, 0) in direction of $Q_{z=0}$ is strictly negative if and only if (iff):

$$A > \overline{A} := \frac{d\overline{Y}_2^N}{\overline{L}^N - 1} \tag{17}$$

strictly positive iff the opposite of (17) holds. The eigenvalue in direction of $Q_{x=0}$ is strictly negative iff:

$$B > \overline{B} := \frac{e\overline{Y}_2^S}{\overline{L}^S - 1} \tag{18}$$

strictly positive iff the opposite of (18) holds.

[9] The proof of Proposition 1 (and of the Propositions 2 and 3 that follow) implies some simple mathematical passages and will be omitted here for space reasons. The proof, however, is available from the authors upon request.

It follows that the fixed point (0, 0) (where all agents work low in both hemispheres) is (locally) attracting if A and B are high enough (conditions (17)–(18)).

Similar conditions can be obtained for the other vertices of the square Q. In particular, the fixed point (1, 1) (where all agents work high in both hemispheres) is attracting if A and B are low enough, namely:

$$A < \overline{A} + \alpha \overline{Y}_2^N + \delta \overline{Y}_2^S$$
$$B < \overline{B} + \gamma \overline{Y}_2^N + \beta \overline{Y}_2^S$$

The fixed point (0, 1) (where all Northern agents work low and all Southern agents work high) is attracting if the following conditions are satisfied:

$$A > \overline{A} + \delta \overline{Y}_2^S$$
$$B < \overline{B} + \beta \overline{Y}_2^S$$

Finally, the fixed point (1, 0) (where all Northern agents work high and all Southern agents work low) is attracting if it holds:

$$A < \overline{A} + \alpha \overline{Y}_2^N$$
$$B > \overline{B} + \gamma \overline{Y}_2^N$$

The results above are intuitively appealing. If B is relatively low, i.e. if the amount of natural resources that are left in the South after subsistence production of $\overline{Y}_1$ is relatively low,[10] Southern people will decide to work high in order to replace consumption of the depleted environment with the substitution consumption of $\bar{Y}_2(z = 1$ is attracting). On the contrary, if natural resources that are left in the South after production of $\bar{Y}_1$ are relatively high, Southern people will then prefer to work low and enjoy their environment ($z = 0$ is attracting). A similar interpretation applies to the North: if A is sufficiently low, Northern agents are induced to work high to replace their own depleted environment ($x = 1$ is attracting), while if A is sufficiently high they do not have such an incentive and will prefer to work low ($x = 0$ is attracting).

The following proposition concerns the stability properties of the fixed points belonging to the interior of the edges of the square Q.

Proposition 2 *The Jacobian matrix of the system* (14) *evaluated at the fixed points in the interior of the edges* $Q_{x=i} (i = 0, 1)$ *is*:

$$\begin{bmatrix} (1-2i)\Delta P^N(i, \overline{z}) & 0 \\ \overline{z}(1-\overline{z})\frac{\partial \Delta P^S(i,\overline{z})}{\partial x} & \overline{z}(1-\overline{z})\frac{\partial \Delta P^S(i,\overline{z})}{\partial z} \end{bmatrix}$$

where $\overline{z}$ *is the value of* z *at the fixed point, and has eigenvalues:* $\overline{z}(1-\overline{z})\frac{\partial \Delta P^S(i,\overline{z})}{\partial z}$ (*in direction of* $Q_{x=i}$) *and* $(1-2i)\Delta P^N(i, \overline{z})$ (*in direction of the interior of* Q).

[10] Remember that $A := \overline{E}^N - \alpha \bar{Y}_1^N - \delta \bar{Y}_1^S$ and $B := \overline{E}^S - \beta \bar{Y}_1^S - \gamma \bar{Y}_1^N$.

The Jacobian matrix of the system (14) *evaluated at the fixed points in the interior of the edges* $Q_{z=i}(i=0,1)$ *is*:

$$\begin{bmatrix} \overline{x}(1-\overline{x})\frac{\partial \Delta P^N(\overline{x},i)}{\partial x} & \overline{x}(1-\overline{x})\frac{\partial \Delta P^N(\overline{x},i)}{\partial z} \\ 0 & (1-2i)\Delta P^S(\overline{x},i) \end{bmatrix}$$

where $\overline{x}$ *is the value of* x *at the fixed point, and has eigenvalues:* $\overline{x}(1-\overline{x})\frac{\partial \Delta P^N(\overline{x},i)}{\partial x}$ (*in direction of* $Q_{z=i}$) *and* $(1-2i)\Delta P^S(\overline{x},i)$ (*in direction of the interior of* Q).

Note that, given a fixed point in an edge $Q_{j=i}$, $j=x,z$ and $i=0,1$, the sign of its eigenvalue in direction of $Q_{j=i}$ is negative if and only if the fixed points at the extrema of $Q_{j=i}$ have positive eigenvalues in direction of $Q_{j=i}$.

The following proposition analyses the stability of the fixed point in the interior of the square Q.

Proposition 3 *The Jacobian matrix of the system* (14) *evaluated at a fixed point* $(\overline{x},\overline{z})$ *in the interior of* Q (*i.e.* $0<\overline{x},\overline{z}<1$) *is*:

$$\begin{bmatrix} \overline{x}(1-\overline{x})\frac{\partial \Delta P^N(\overline{x},\overline{z})}{\partial x} & \overline{x}(1-\overline{x})\frac{\partial \Delta P^N(\overline{x},\overline{z})}{\partial z} \\ \overline{z}(1-\overline{z})\frac{\partial \Delta P^S(\overline{x},\overline{z})}{\partial x} & \overline{z}(1-\overline{z})\frac{\partial \Delta P^S(\overline{x},\overline{z})}{\partial z} \end{bmatrix} \tag{19}$$

where the sign of the determinant of (19) *is equal to the sign of the expression*:

$$\alpha\beta-\gamma\delta \tag{20}$$

and the trace of (19) *is equal to*:

$$\overline{x}(1-\overline{x})\alpha\overline{Y}_2^N(\overline{L}^N-1)+\overline{z}(1-\overline{z})\beta\overline{Y}_2^S(\overline{L}^S-1) \tag{21}$$

The above proposition says that if the expression (20) is strictly negative, then the interior fixed point is a saddle (i.e. it is unstable). If the opposite holds, the fixed point may be a source (i.e. repulsive) or a sink (i.e. attractive); in particular, since $\alpha>0$ and $\beta>0$, the trace (21) is strictly positive and consequently the interior fixed point is a source.

4 Dynamics of the economy

Let us first recall that above (15) (respectively, above (16)) it holds $\dot{x}>0(\dot{z}>0)$, viceversa below (15) (respectively, below (16)). The signs of $\dot{x}$ and $\dot{z}$ are due to the fact that, in this context, defensive expenditures have a self-enforcing character: the higher is the proportion of individuals choosing to self-protect from environmental degradation in both hemispheres, the higher is the incentive to self-protect. Notice that the line corresponding to Eq. (15) (respectively, (16)) moves upwards as A (respectively, B) grows. If $A(B)$ is sufficiently high, it always holds $\dot{x}<0(\dot{z}<0)$ for every possible value of x and z; the opposite holds if $A(B)$ is sufficiently low.

The following proposition describes the dynamics of the economy.

Proposition 4 *The dynamics of the system* (14) *has the following features*:

a) *Every trajectory of the system approaches a fixed point.*
b) *Only the fixed points* $(0, 0)$, $(0, 1)$, $(1, 0)$, $(1, 1)$ *can be attractive.*

Proof The proof of point (b) is straightforward and follows immediately from local stability analysis in the preceding section. To prove point (a) we have to show that limite cycles cannot exist (see e.g. Lefschetz 1997, pp 230, ff.). This is obviously the case when the interior fixed point $(\overline{x}, \overline{z})$, $0 < \overline{x}, \overline{z} < 1$, does not exist or, when existing, it is a saddle point. If $(\overline{x}, \overline{z})$ is a source, then $\alpha\beta - \gamma\delta > 0$ (see (20)), that is the straight line (15), where $\dot{x} = 0$, crosses the straight line (16), where $\dot{z} = 0$, from above. In such case, it is easy to see that the regions of Q where $\dot{x}$ and $\dot{z}$ have the same sign are positively invariant; this implies that no oscillatory behavior of trajectories may occur. □

Remark 1 Observe that the vertices of Q can be simultaneously attractive; this is the case when the following conditions hold:

$$\overline{A} + \delta\overline{Y}_2^S < A < \overline{A} + \alpha\overline{Y}_2^N \tag{22}$$

$$\overline{B} + \gamma\overline{Y}_2^N < B < \overline{B} + \beta\overline{Y}_2^S \tag{23}$$

where $\overline{A} := \frac{d\overline{Y}_2^N}{\overline{L}^N - 1}$ and $\overline{B} := \frac{e\overline{Y}_2^S}{\overline{L}^S - 1}$. Necessary conditions for (22) and (23) are $\delta\overline{Y}_2^S < \alpha\overline{Y}_2^N$ and $\gamma\overline{Y}_2^N < \beta\overline{Y}_2^S$.

Figure 1 shows the dynamics emerging when conditions (22) and (23) are both simultaneously satisfied, with attractive fixed points represented by full dots (•) and repulsive ones by open dots (∘). As the figure shows, in this case all vertices of Q are attractive, all other fixed points along the sides of Q are saddle points and the fixed point inside Q is a source. The attraction basins of the vertices are delimited by the stable manifolds of the saddle points in the interior of the sides of Q.

From Proposition 4 and the Remark above, it follows that all possible dynamic regimes can be classified according to the number of vertices of Q that are simultaneously attractors (from one to four). At any attractive vertex each hemisphere selects only one of the two strategies (l^j, h^j) with $j = N, S$ so that all agents choose to work either low or high within the same hemisphere.

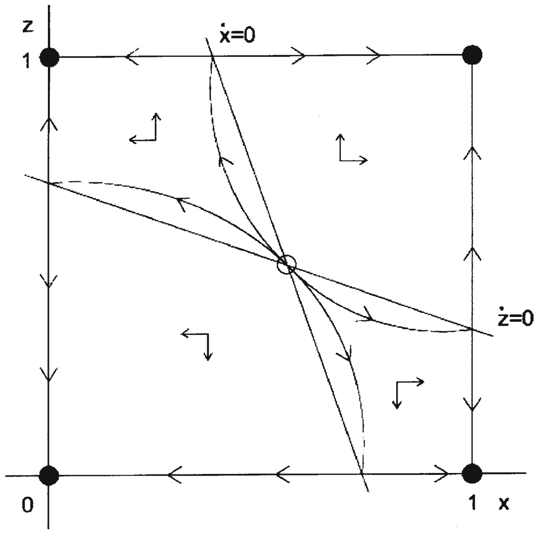
5 Well-being analysis

In this section we will examine the average well-being level in the North and in the South, which are equal to, respectively:

$$\overline{P}^N(x, z) := xP_h^N(x, z) + (1 - x)P_l^N(x, z)$$

$$\overline{P}^S(x, z) := zP_h^S(x, z) + (1 - z)P_l^S(x, z)$$

Fig. 1 Dynamics of the model when all vertices are simultaneously attracting



Observe that $\overline{P}^N(0,z) = P_l^N(0,z)$ and $\overline{P}^N(1,z) = P_h^N(1,z)$ are the Northern average well-being levels when everyone works low and high in the North, respectively. Similarly, for the South we have $\overline{P}^S(x,0) = P_l^S(x,0)$ and $\overline{P}^S(x,1) = P_h^S(x,1)$.

The following proposition applies.

Proposition 5 *For the population of the North the fixed point* $(0,0)$ *always Pareto-dominates all the other fixed points in Q with* $0 \le x < 1$ *(provided they exist), for any z, that is:* $\overline{P}^N(0,0) > \overline{P}^N(x,z) \forall x \in [0,1)$ *and* $\forall z \in [0,1]$.

Mutatis mutandis, the same applies to the South: $\overline{P}^S(0,0) > \overline{P}^S(x,z) \forall z \in [0,1)$ *and* $\forall x \in [0,1]$.

Furthermore, if $A > \overline{A} - \frac{\alpha \bar{Y}_2^N}{\bar{L}^N - 1}$ *in the North* ($B > \overline{B} - \frac{\gamma \bar{Y}_2^S}{\bar{L}^S - 1}$ *in the South, respectively), the fixed point* $(0,0)$ *Pareto-dominates also the fixed points with* $x = 1 (z = 1)$ *and the fixed point* $(1,1)$ *is Pareto-dominated by all the other fixed points.*

Proof To prove the first part of the proposition, we have to show that average payoff of the North, evaluated in $(0,0)$, is higher than in any point $(\bar{x}, \bar{z})$ along the line $\Delta P^N(x,z) = 0$ and along the side $Q_{x=0}$. The average payoff level in $(0,0)$ is:

$$\overline{P}^N(0,0) = P_l^N(0,0) = \ln(1 - L_l^N) + \ln \bar{Y}_1^N + \ln A$$

Suppose $(\bar{x}, \bar{z}) \in \Delta P^N(x,z) = 0$. Then it holds $P_h^N(\bar{x}, \bar{z}) = P_l^N(\bar{x}, \bar{z})$, which implies:

$$\overline{P}^N(\bar{x}, \bar{z}) = P_l^N(\bar{x}, \bar{z}) = \ln\left(1 - L_l^N\right) + \ln \bar{Y}_1^N + \ln\left(A - \alpha \bar{Y}_2^N \bar{x} - \delta \bar{Y}_2^S \bar{z}\right)$$

Therefore, if $\bar{x}$ and/or $\bar{z} > 0$, it follows that: $\overline{P}^N(0,0) > \overline{P}^N(\bar{x}, \bar{z})$. Thus, average payoff in $(0,0)$ is higher than in any fixed point in the interior of Q and in any fixed point in the interior of the sides $Q_{z=i}(i = 0, 1)$. Furthermore, it is easy to check that $(0,0)$ always Pareto-dominates any fixed point in the side $Q_{x=0}$. It remains to prove that $(0,0)$ Pareto-dominates any fixed point in the side $Q_{x=1}$ if $A > \overline{A} - \frac{\alpha \bar{Y}_2^N}{\overline{L}^N - 1}$. It is obvious that $(1,0)$ always Pareto-dominates any other fixed point in the side $Q_{x=1}$. Since the vertex $(1,0)$ always Pareto-dominates any other fixed point along the side $Q_{x=1}$, it is sufficient to prove that when $A > \overline{A} - \frac{\alpha \bar{Y}_2^N}{\overline{L}^N - 1}$ the well-being in $(0,0)$ is higher than in $(1,0)$, which is actually the case as can be easily verified by very simple computations.

With similar arguments, it is easy to check that $(1,1)$ is Pareto-dominated by all the other fixed points when $A > \overline{A} - \frac{\alpha \bar{Y}_2^N}{\overline{L}^N - 1}$.

The proof of the part of the proposition concerning well-being in the South is identical. □

By the above proposition, remembering the threshold values given in Proposition 1, it is easy to see that when the fixed point $(0,0)$ is locally attracting, then it Pareto-dominates the other ones. Furthermore, the fixed point $(0,0)$ may Pareto-dominate the fixed point $(1,1)$ (in both hemispheres) even if $(1,1)$ is the unique attracting fixed point, provided A and B are sufficiently large, namely, provided the flow of the environmental good that is left in the North and in the South, respectively, after subsistence production of $\bar{Y}_1$ in both hemispheres is sufficiently high; in such case, economic growth in both hemispheres (i.e. an increase in the aggregate production level) reduces well-being as we pass from the repulsive point $(0,0)$ to the attractive point $(1,1)$. If so, the increase of production and consumption leads to a Pareto worsening.

It is easy to check that if $(0,0)$ does not Pareto-dominate all the other fixed points (in the North and in the South), then the dynamics (14) is trivial, i.e. $\dot{x}$ and $\dot{z}$ are always positive in Q. In such case, the fixed point $(1,1)$ is globally attracting and Pareto-dominates any other possible state (x, z) in the North and in the South.

From the well-being analysis above, it follows that:

Remark 2 In Fig. 1 each hemisphere achieves its highest well-being level in $(0,0)$, therefore only one of the four possible vertices selected by the dynamics implies the maximum well-being level. Furthermore, the lowest well-being level is achieved in $(1,1)$, while intermediate levels are reached in $(0,1)$ and $(1,0)$.

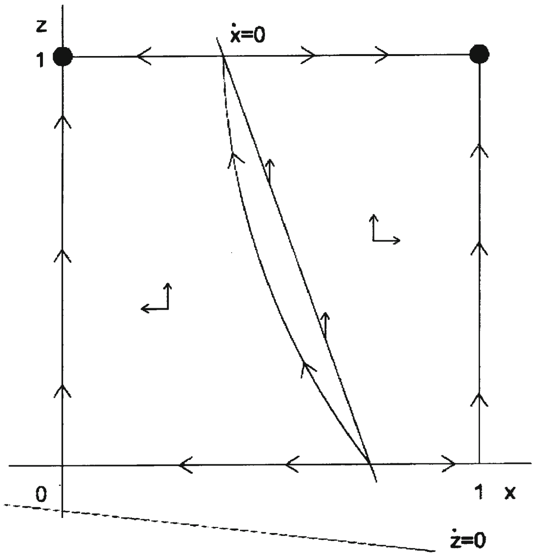
Notice that if x and/or z get sufficiently low, the dynamics of the model will lead away from $(1,1)$, namely, from the worst attracting fixed point. In other words, in order to get out of the "poverty trap" where both hemispheres have the lowest possible well-being level, it would be sufficient that one hemisphere unilaterally managed to lower its self-protecting choices below a certain threshold level. This suggests that a unilateral environmental policy that reduces the need for self-protection choices in one hemisphere (for instance, in the developed countries) could have positive welfare effects in both hemispheres and thus for the world as a whole, especially in the case of global environmental problems that generate a the strict interdependence between the North and the South.

6 Environmental dumping and North-South feedback effects

One of the most debated issues in the environmental literature concerns the possibility that introducing stricter environmental policies in the North may lead Northern industries to move polluting productions to the South where ecological regulations are less severe. To what extent such mechanism, known as environmental dumping, takes place in reality is still a matter of investigation in the empirical literature. In the case of worldwide problems like global warming, however, shifting polluting productions to the South may generate negative feedback effects on the North that counterbalance Northern ecological policies. The effects of environmental dumping can be examined in our model by simple comparative dynamics analysis. If the most polluting productions move from the North to the South, the impact of Northern production on Northern environment (the parameter α in the model) will fall, whereas its impact on Southern environment (the parameter γ) will rise.[11] The same applies if the North transfers to the South toxic wastes that result from its production. Similarly, if the North shifts to the South its exploitation of natural resources used as inputs in the production process, the environmental impact of Northern production is also transferred from the North to the South. Think, for instance, of deforestation induced in the South by paper production in the North, or of exploitation of biodiversity in the South for the pharmaceutical production in the North. All these cases may be analysed by looking at the combined effect of reducing α and increasing γ in our model. A reduction in α improves Northern environmental quality. An increase in γ, on the contrary, worsens Southern environmental quality stimulating environmental defensive expenditures and thus also aggregate production, which has a negative feedback effect on Northern environmental quality. Hence, the final effect on Northern environment and well-being of transferring negative externalities to the South is a priori undetermined. The possible consequences of this policy can be exemplificated by looking at the dynamics showed in Fig. 1. Recall that in this case the fixed point $(0, 0)$ Pareto-dominates all other vertices, while $(1, 1)$ is Pareto-dominated by all of them; all vertices are locally attractive. An increase in γ -ceteris paribus- may cause the instability of the fixed points in the edge $Q_{z=0}$ (see Proposition 1) giving rise to the dynamic regime represented in Fig. 2. If so, the fixed point $(0, 0)$ with the highest well-being level is no longer attractive, while that with the lowest well-being level $(1, 1)$ is still a sink. Transferring the environmental impact of Northern production to the South, therefore, has ambiguous effects on the Northern well-being and, as shown in this case, it might end up decreasing well-being in both hemispheres.

[11] We are implicitely assuming that Northern industries spend or reinvest in the North the profits from producing in the South. Production in the South of Northern industries can be considered, therefore, as Northern production as it increases Northern income. If, on the contrary, the profits of this polluting activities remain in the South, environmental dumping will cause the impact of Southern production on its environment (β) to rise leaving γ unchanged.

Fig. 2 Dynamics of the model after transferring the environmental impact from the North to the South



7 Conclusions

Nowadays an increasing number of people make defensive expenditures to protect against the deterioration of the environment they live in. This phenomenon, that leads to the substitution of depleted common access environmental goods with privately produced substitute goods, is becoming more and more frequent in modern industrialised economies. This observation has recently induced some studies to examine the relationship between environmental defensive expenditures and economic growth. The basic idea underlying these works is that negative externalities could contribute to a self-reinforcing growth process: environmental degradation induces individual defensive expenditures that raise the activity level which, in turn, may further increase environmental degradation.

The present paper builds on this literature by extending the analysis from a single population to a North-South context. The aim of the paper is to investigate the possible feedback effects that environmental defensive expenditures may generate between the two hemispheres and their impact on growth and welfare in rich and poor countries. We show that growth is characterised in the model by "critical mass" or "imitation" effects. If a sufficiently high number of agents in one hemisphere choose to work hard, the other agents living in that hemisphere are induced to choose the same strategy, with an overall growth in the activity and production level. If, on the contrary, the number of "lazy" agents is sufficiently high, the others will also be induced to work little. These feedback effects may determine an undesirable (i.e. welfare-reducing) increase in the activity levels. Both hemispheres, in fact, may end up in a situation where everyone works "too much": people work harder to protect themselves against pollution, but they might be better-off by working less and enjoying a cleaner world. Calling $x(z)$ the quota of population that works hard and makes defensive expenditures in the North (South), the fixed point where everyone works little ($x = 0$, $z = 0$) may Pareto-dominate any other (x, z) pair for both hemispheres.

Finally, we show that transferring the environmental impact of Northern production to the South (e.g. transferring polluting activities, production waste, exploitation of natural resources etc.) may end up decreasing welfare in both hemispheres.

Notice that the results that descend from the model would apply a fortiori if we relaxed the simplifying (and over-optimistic) assumption that the natural resource can regenerate instantaneously. As a matter of fact, the regeneration process of any depleted environmental stock takes time (provided the environmental damage is not irreversible so that the natural resource can be renewed). In reality, therefore, the lower the regenerative capacity of the environment, the higher the need for substitute goods to replace the depleted environmental good. This tends to increase the agents' incentive to work hard to afford self-protection choices, which increases in its turn the overall production level and the consequent environmental damages, thus further reinforcing the vicious circle described in the paper.

We are fully aware that the results emerging from this work may appear provocative, but we believe that they could contribute to shed light on some aspects of economic growth that have generally been neglected in the literature. Further research will obviously be needed to deepen the present analysis. In particular, it would be interesting to allow for population changes deriving from migration flows between the two hemispheres for economic reasons (e.g. poverty and unemployment in the country of origin) as well as for ecological reasons (environmental degradation or ecological catastrophes as in the case of the environmental refugees mentioned at the beginning). We leave this issue for future research.

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