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CAN EDUCATION BE GOOD FOR BOTH GROWTH AND THE ENVIRONMENT?

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We develop an overlapping-generations model of growth and the environment in relation to public policy on education. Beyond the traditional mechanisms through which knowledge, growth, and the environment interplay, we stress the role played by education in environmental awareness. Assuming first that environmental awareness is constant, we show the existence of a balanced-growth path (BGP) along which environmental quality increases continually. Then, if education enhances environmental awareness, the equilibrium properties are modified: the economy can reach a steady state or converge to an asymptotic BGP. Therefore, education does not necessarily promote sustained and sustainable growth.

Keywords: Overlapping Generations, Public Education, Environmental Maintenance, Green Awareness, Sustainable Growth

1. INTRODUCTION

Over the past twenty years, the literature on growth and the environment has increased substantially [see Brock and Taylor (2005) and Xepapadeas (2005)], and human capital accumulation, through education, has been identified as one necessary ingredient for sustainable growth. Education was first recognized as a

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key determinant of economic growth [see Krueger and Lindhal (2001) for a review of theoretical and empirical evidence]. In Lucas's (1988) seminal paper, agents can improve their skills by devoting time to education. The accumulation of human capital enhances the productivity of labor and allows the economy to experience sustained growth. In an overlapping-generations model, Azariadis and Drazen (1990) explain the emergence of a poverty trap by the existence of threshold effects in education. In these papers, time spent in education depends on private agents' decisions. However in a similar framework, Glomm and Ravikumar (1997) assume that education is financed by public expenditures. The authors emphasize the impact of education policy on growth. Their main result is that taxing revenues to finance education and the accumulation of knowledge stimulates long-term growth as long as the tax rate does not exceed the share of human capital in production.

To understand why education and human capital accumulation are also good for the environment, some authors have dissected the link between education, growth, and the environment. Gradus and Smulders (1993) review the consequences of introducing environmental concern into both exogenous and endogenous growth models. In particular, by adding a flow of pollutant and abatement to Lucas' model, they show that sustained growth remains the rule in the long run. It turns out that the constant growth rate of the economy is in fact independent of the degree of environmental concern. Even though care for the environment crowds out investment in physical capital (the polluting input), this effect is exactly offset by the replacement of physical capital by human capital (the clean input). Vellinga (1999) gets the same result with a model extended by a stock of pollutant and with separability in utility between consumption and the environment. Within an overlapping-generations model à la Blanchard (1985), Pautrel (2011) asks whether environmental policy may have a positive impact on long-term growth. In his setting the growth rate of the economy depends on the environmental tax. Then, under certain conditions, a *win–win* situation occurs, in which increasing the tax rate also benefits growth by providing households with greater incentives for education.

In all this literature, the positive impact of education on growth and the environment is taken for granted. That is not disputable. However, when the relationship between education-driven growth and the environment is assessed, one important part of the story is somehow missing: the interdependence between education and environmental concern. The purpose of our paper is to deal with this issue.

The essence of this idea lies in the influence of education on agents' environmental concern. There exists a vast literature supporting such a relationship, either from empirical studies or from sociology. One of the very first survey trying to explain the motives for environmental concern is Van Liere and Dunlap (1980). They show that the level of education is one candidate for explaining environmental concern, among other candidates such as age, income, residence, sex, and political opinions. In a recent econometric analysis, Franzen and Meyer (2010) show that education (measured as the number of years respondents spent in school) is one of the most prominent factor explaining environmental concern. The rationale they provide is that, "in order for environmental quality to influence environmental concern, individuals must be able to assess the quality of the environment. Such knowledge is usually acquired through education, and thus a country's educational level should be positively linked to environmental concern." A survey by the European Commission also emphasizes the link between the level of education and environmental concern. This study reveals that the longer the respondent has spent in full-time education, the better informed he or she feels.[1] The higher the education level, the more strongly the relationship between environmental quality and quality of life is perceived. Furthermore, as environmental awareness increases, so does the acceptability of regulation: "the higher the respondent's level of education, the more he or she values the importance of making stricter regulations" [EC (2005, p. 37)].[2]

Even though the rationale behind such an idea is hardly disputable, the macroeconomic consequences and environmental effectiveness of educational policies have not yet been explored from a theoretical perspective. Can countries really shape economic growth by greening agents' preferences? In which direction would such changes lead the economy? Could they be beneficial to both economic growth and environmental quality?

These questions are addressed within an overlapping generations model (OLG) of public expenditure on education à la Glomm and Ravikumar (1997). We extend this framework by introducing the environment. Economic activity generates, as a by-product, polluting emissions that degrade the quality of the environment. Private agents, whose welfare depends on environmental quality and consumption, have the opportunity to devote part of their resources to environmental maintenance. In this respect, our model also extends the OLG model developed by John and Pecchenino (1994). As regards preferences about the environment, we follow Ono (2003) by defining environmental concern or awareness as the elasticity between consumption and environmental quality. The literature on endogenous growth and the environment states that constant awareness is a necessary condition for sustainable balanced growth.[3] We depart from the literature by assuming that environmental concern is endogenous, recognizing that agents' awareness is positively influenced by education.

The analysis of an economy growth prospects is substantially modified. If awareness depends on the level of human capital, then agents' tradeoffs change toward more environmentally friendly decisions as they accumulate knowledge. As a result, we show that multiple long-run equilibria of different natures coexist. The economy may then either reach a steady state or follow an asymptotic balanced-growth path (BGP) in the long run. It is worth noting that the economy converges to the asymptotic BGP when environmental concern approaches a constant value. Thus, it has the same qualitative features as the BGP one would obtain under the usual assumption of constant environmental concern. Actually, this case can be seen as a particular case of our more general framework with endogenous environmental concern. To understand which of these two equilibria will be reached by the economy in the long run, the stability properties of the model are scrutinized. When the sensitivity of environmental awareness to knowledge is low, the economy may be driven toward an asymptotic BGP. However, if environmental awareness is very sensitive to human capital, then it substantially affects the dynamics of the economy and may drive it to a steady state.

The impact of education policy on the macroeconomy and the environment depends once again on the nature of the long-run equilibrium. Along the asymptotic BGP, we can generalize the main conclusion of Glomm and Ravikumar (1997) that improving education allows the economy to enjoy higher growth and a better environment, provided the tax rate is initially below the share of human capital in output. In the steady state, higher taxation does not necessarily enhance wealth (as measured by output) or environmental quality, even if the tax rate is initially below the share of human capital in output. Indeed, endogenous concern now plays a role, because higher education means higher incentives to maintain the environment at the expense of productive savings. We can, however, find a sufficient condition according to which the tax rate should be low enough for the result that more education is beneficial to output and the environment. We finally investigate how public policy can affect the growth prospects of the economy, through its influence on endogenous environmental awareness. We notably show that if the policy maker seeks to promote sustained growth in the long run, then there exists a rule for the setting of her instruments that allows the economy to avoid the limit to growth induced by convergence to the steady state.

The remainder of the paper is as follows. Section 2 presents the model. Section 3 examines the features of the intertemporal competitive equilibrium and notably shows the existence of two different outcomes: the asymptotic BGP and the steady state. The discussion about stability is also presented. The policy analysis is proposed in Section 4. We first perform some comparative statics, and then scrutinize the impact of public policy on growth prospects through environmental awareness. Finally, our conclusions are summarized in Section 5.

2. THE MODEL

The present framework is an OLG model that combines consideration of growth, knowledge, and the environment. In a perfectly competitive world, the firms produce a single homogeneous good used both for consumption and for investment. In addition, the use of physical capital in production generates polluting emissions. The government levies an income tax to finance education.

2.1. Production

Firms produce the final good Y_t with a constant–returns to scale technology using skilled labor L_t^s and physical capital K_t,

$$Y_t = F\left(K_t, L_t^s\right), \tag{1}$$

where L_t^s is equal to the stock of human capital H_t times the amount of unskilled labor L_t. Because the production function is homogeneous of degree one, it can be expressed by its intensive form, $f(k_t)$, with $k_t = K_t/L_t^s$ being the capital–skilled labor ratio.

Assumption 1. $f(k) : R^+ \to R^+$ is C^2. $f(0) = 0, \forall k > 0, f(k) > 0, f'(k) > 0, f''(k) < 0$. There exists an upper bound to the attainable capital $\hat{k} < \infty$ such that $f(\hat{k}) = \hat{k}$. In addition, $\lim_{k\to+\infty} f(k) = +\infty$ and $\lim_{k\to+\infty} f'(k) = 0$.

Assuming capital depreciates at a rate $\delta \in [0, 1]$, profit maximization yields

$$w_t = f(k_t) - k_t f'(k_t), \tag{2}$$

$$r_t = f'(k_t) - \delta, \tag{3}$$

with w_t the wage rate and r_t the real rental rate of capital.

2.2. The Households

We consider an infinite-horizon economy composed of finite-lived agents. A new generation is born in each period $t = 1, 2, \ldots,$ and lives for two periods: youth and old age. There is no population growth and the size of a generation is normalized to one. The young agent born in period t is endowed with H_t units of human capital. As in Glomm and Ravikumar (1997), the stock of knowledge accumulates according to the constant-returns process

$$H_{t+1} = G(H_t, E_t), \tag{4}$$

with E_t the amount of public expenditure on education at period t. Defining e_t as the ratio from public expenditure to knowledge, this technology can be rewritten as $H_{t+1} = H_t g(e_t)$.

Assumption 2. $g(e) : R^+ \to R^+$ *is* C^2. $g(0) = 0, \forall e > 0, g(e) > 0, g'(e) > 0, g''(e) < 0$. Moreover, $\lim_{e\to+\infty} g(e) = +\infty$.

Education is thus entirely financed by public expenditures. In that purpose the government taxes both labor income and the interest on savings at an uniform tax rate τ.

In her youth, the agent supplies knowledge H_t to firms for a real wage $w_t H_t$. She allocates this wage net of taxes to savings s_t and maintenance m_t, taking as given the tax rate τ. When retired, the agent supplies her savings to firms and earns the return of savings $R_{t+1}s_t$ [with $R_{t+1} = 1 + (1-\tau)r_{t+1}$ being the interest factor]. Her income is entirely devoted to consumption c_{t+1}. The two budget constraints are respectively

$$(1-\tau)w_t H_t = s_t + m_t, \tag{5}$$

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$$c_{t+1} = [1 + (1-\tau)r_{t+1}]s_t. \tag{6}$$

We further assume that the government's budget, at period t, is balanced:

$$E_t = \tau(w_t H_t + r_t s_{t-1}). \tag{7}$$

Polluting emissions are imputed to the use of physical capital and degrade environmental quality Q. It is possible to control the level of emissions and to improve environmental quality through maintenance m_t. The dynamics of Q is then given by

$$Q_{t+1} = (1-\mu)Q_t - \rho K_t + \gamma m_t. \tag{8}$$

The variable Q is a broadly defined index of the quality of the environment whose autonomous level (the level in the absence of human activity) is zero. Then $\mu \in (0, 1)$ is the speed at which Q goes back to its autonomous level and $\rho > 0$ (respectively, $\gamma > 0$) is the parameter that represents the effect of emissions on environmental quality (respectively, the efficiency of maintenance).

In the vein of John and Pecchenino (1994), the preferences of the agent born at date t are defined over old age consumption c_{t+1} and environmental quality Q_{t+1}. This is actually the typical way of catching the trade-off between private consumption and the public good in OLG models with the environment. Our purpose is to go beyond this standard representation of preferences by introducing the link between the education level and agents' concern for the environment. An interesting and original approach to modeling environmental awareness consists in recognizing that agents' tradeoffs and decisions are influenced by the level of knowledge, particularly when these decisions encompass an environmental dimension. Indeed, one may expect that, with knowledge accumulation, private agents' tradeoffs evolve toward environmentally friendly decisions. In other words, the more educated the agents, the greener their actions. This is consistent with the empirical evidence reported in the Introduction.

Considering that environmental awareness is shaped by education leads us to add another argument to the utility function: the level of human capital or knowledge. Thus, the preferences are described by a utility function $U(c_{t+1}, Q_{t+1}, H_{t+1})$ with the following properties:

Assumption 3. $U(c, Q, H) : R^{3+} \to R$ is C^2. Properties with respect to c and Q are as follows: $U_c, U_Q \geq 0$, $U_{cc}, U_{QQ} \leq 0$, and $\lim_{c\to 0} U_c(c, Q) = +\infty$. The cross derivative is positive $U_{cQ} \geq 0$.

H affects preferences only through its influence on environmental awareness $\eta(H)$. Environmental awareness is defined as the elasticity between consumption and environmental quality,

$$\eta(H) = \frac{QU_Q}{cU_c}. \tag{9}$$

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The specific class of utility functions we consider are those that otherwise would be characterized by constant elasticity and constant environmental awareness (CEA).[4]

Preferences with education-led environmental awareness (ELEA) are such that $\lim_{H\to 0}\eta(H) = \underline{\eta} > 0$, $\eta'(H) > 0$, $\eta''(H) \leq 0$, *and* $\lim_{H\to\infty}\eta(H) = \bar{\eta}$ with $\underline{\eta} < \bar{\eta} < \infty$.[5]

Environmental awareness grows at a decreasing rate with knowledge. There exists an upper bound for the weight of the environment in preferences. Even if knowledge can potentially grow indefinitely, environmental awareness asymptotically converges to a level of full awareness of environmental issues. It must be kept in mind that, in this model, the agent cannot influence her own environmental awareness.

CEA preferences can be seen as a special case of ELEA preferences with η constant for all t. The CEA case will serve as a benchmark for our analysis because CEA preferences are typically used in the papers that tackle sustainable growth [see for instance Bovenberg and Smulders (1995, 1996) and Bovenberg and de Mooij (1997)].

In the general ELEA case, the representative agent born at date t divides her resources between maintenance and savings in order to maximize her lifetime utility. Taking prices and pollution at the beginning of period t as given, the problem is written as

$$\max_{m_t, s_t, c_{t+1}} U(c_{t+1}, Q_{t+1}, H_{t+1})$$

subject to

$$\begin{cases} (1-\tau)w_t H_t = s_t + m_t, \\ c_{t+1} = (1 + (1-\tau)r_{t+1})s_t, \\ Q_{t+1} = (1-\mu)Q_t - \rho K_t + \gamma m_t, \\ m_t \geq 0. \end{cases}$$

The first-order condition (FOC) for the representative agent's problem is

$$\begin{aligned} &-R_{t+1}U_1(c_{t+1}, Q_{t+1}, H_{t+1}) + \gamma U_2(c_{t+1}, Q_{t+1}, H_{t+1}) \leqq 0, \\ &m_t[-R_{t+1}U_1(c_{t+1}, Q_{t+1}, H_{t+1}) + \gamma U_2(c_{t+1}, Q_{t+1}, H_{t+1})] = 0. \end{aligned} \quad \textbf{(10)}$$

Let us now define the competitive equilibrium.

DEFINITION 1 (Intertemporal Competitive Equilibrium). *Given the public policy in education, an intertemporal competitive equilibrium is a sequence of per capita variables* $\{c_t, m_t, s_t\}$*, aggregate variables* $\{K_t, H_t, Q_t, E_t\}$*, and prices* $\{w_t, r_t\}$ *such that*

(i) *households and firms are at their optimum: the FOC (10) and the two conditions (2) and (3), for profit maximization, are satisfied;*
(ii) *all markets clear:* $L_t = 1$ *implying* $L_t^s = H_t$ *and* $K_{t+1} = s_t$*;*
(iii) *individual budget constraints (5) and (6) are satisfied;*
(iv) *the government budget (7) is balanced;*
(v) *the dynamics of human capital is given by (4);*
(vi) *the dynamics of environmental quality is given by (8).*

3. COMPETITIVE EQUILIBRIUM

In this section, an equilibrium analysis will be conducted for the general case where preferences exhibit ELEA.[6]

When agents engage in environmental maintenance, the FOC (10) defines, at any date, a relationship between environmental quality and human and physical capital,

$$Q_{t+1} = \gamma\eta(H_{t+1})H_{t+1}k_{t+1}. \tag{11}$$

From now on, we assume that capital does not depreciate: $\delta = 0$. Then, under conditions (2) and (3), the government's revenue is expressed as a share of production,

$$\tau(w_t H_t + r_t s_{t-1}) = \tau H_t f(k_t),$$

which implies that the dynamics of H simplifies to

$$H_{t+1} = H_t g[\tau f(k_t)]. \tag{12}$$

Finally, the maintenance decision is

$$m_t = (1-\tau)H_t[f(k_t) - k_t f'(k_t)] - H_{t+1}k_{t+1}. \tag{13}$$

Putting equations (11)–(13) together, equilibrium dynamics is given by the following system:

$$\begin{cases} Q_{t+1} = \gamma\eta(H_{t+1})H_{t+1}k_{t+1}, \\ H_{t+1} = H_t g[\tau f(k_t)], \\ Q_{t+1} = (1-\mu)Q_t - \rho H_t k_t + \gamma\{(1-\tau)H_t[f(k_t) - k_t f'(k_t)] - H_{t+1}k_{t+1}\}. \end{cases} \tag{14}$$

Thereafter, we investigate what kind of outcome may result from (14), in the long run.

DEFINITION 2 (Balanced-Growth Path, Asymptotic Balanced-Growth Path, Steady State.)

- *A BGP is a 4-tuple* $\{\bar{Q}, \bar{H}, \bar{K}, \theta\}$ *such that*

$$\begin{cases} Q_t = \bar{Q}(1+\theta)^t \\ H_t = \bar{H}(1+\theta)^t \\ K_t = \bar{K}(1+\theta)^t \end{cases} \tag{15}$$

solves (14) exactly.

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• *An asymptotic BGP (A-BGP) is a BGP that an economy approaches asymptotically but never reaches.*
• *A steady state is a BGP with $\theta = 0$.*

A BGP is a path where all variables grow at the same constant rate θ. Looking at the dynamical system, it turns out that the ratio between environmental quality and physical capital cannot be kept constant because environmental awareness evolves in response to the accumulation of human capital. Let us now see whether an A-BGP and/or a steady state can exist. Note that an A-BGP occurs when a BGP cannot be reached but is gradually converged to as time goes to infinity. The very characteristics of an asymptotic BGP is that, even if no proper BGP exists, the growth rates of variables of the economy still approach a constant and common value.

Define capital's share of output and the elasticity of substitution between physical and human capital as follows:

$$s(k) = \frac{kf'(k)}{f(k)}. \tag{16}$$

$$\sigma(k) = -\frac{[1 - s(k)]f'(k)}{kf''(k)}. \tag{17}$$

Existence results are stated in two distinct propositions because A-BGP and steady state arise under different conditions.

PROPOSITION 1. *Consider the economy with ELEA preferences. If*

$$\lim_{k \to 0} \frac{f(k) - kf'(k)}{k} > \frac{1}{1 - \tau}, \tag{18}$$

$$\sigma(k) \geq s(k) \ \forall k > 0, \tag{19}$$

and

$$\bar{\eta}(1 - \mu) \geq \frac{\rho}{\gamma}, \tag{20}$$

then there exists a unique A-BGP. [7]

Proof. See Appendix A. ■

Condition (18) is common in the literature that studies the equilibrium properties of the OLG one-sector model (without environmental issues). It is also used in Prieur (2009), which deals with this kind of issue. This condition generalizes *the strengthened Inada condition*, introduced by Galor and Ryder (1989), with a public policy. It ensures that the first unit of capital is sufficiently efficient, in terms of labor productivity [recall that the numerator in (18) corresponds to the wage $w(k)$], thereby avoiding the trivial equilibrium with zero capital. It is also a necessary condition for the existence of a nontrivial equilibrium [see de la Croix and Michel (2000)]. The second condition, (19), states that the elasticity of substitution between capital and labor is higher than the capital share of output. These conditions are notably satisfied by the CES technologies, $F(K, H) = [\alpha K^{-\phi} + (1-\alpha)H^{-\phi}]^{-\frac{1}{\phi}}$, when $\phi \in (-1, 0]$. In addition, the second one seems quite reasonable because most of the estimates of the capital share of output and the elasticity of substitution give values respectively comprised in the range [0.3, 0.4] and close to 1.

The sufficient condition (20) can be interpreted as follows. Let us consider the present generation with high environmental concern $\bar{\eta}$. She is willing to devote a lot of resources to maintain the environmental quality. But this decision is done at the expense of savings and negatively affects capital accumulation. The next generation will, in turn, inherit from a lower stock of capital. The negative income effect will translate again into a reduction of the investment in physical capital. In order to balance this negative effect, the current generation must, at the same time, bequeath an important amount of environmental quality. Indeed, in this situation, the next generation will be able to substitute maintenance for savings. This requires ρ and/or μ (respectively γ) to be low (respectively high). This substitution allows the economy to approach, in the long run, a sustainable growth path.

PROPOSITION 2. *Consider the economy with ELEA preferences. There exists a unique steady state if and only if*

$$(1-\tau)\frac{f(\tilde{k}) - \tilde{k}f'(\tilde{k})}{\tilde{k}} \in \left(\mu\underline{\eta} + 1 + \frac{\rho}{\gamma}, \mu\bar{\eta} + 1 + \frac{\rho}{\gamma}\right) \tag{21}$$

with $\tilde{k}$ the long-run ratio of physical to human capital in the steady state.

Proof. See Appendix B. ■

The existence condition (21) can be understood as defining a range of variation for the tax rate. Actually, for the specific class of Cobb–Douglas and CES production functions, assuming as in Glomm and Ravikumar (1997) that the education technology is Cobb–Douglas, it can easily be shown that $(1-\tau)\frac{f(\tilde{k})-\tilde{k}f'(\tilde{k})}{\tilde{k}}$ is an inverted U-shaped function of the tax rate. Provided that the maximum of this function lies above $\mu\underline{\eta} + 1 + \rho/\gamma$, a range exists such that for any tax rate chosen in this range there exists a unique steady state. We shall come back to this point in the next section, devoted to the role of public policy and its influence on growth prospects.

At this stage, it is worth mentioning what would be the long-run behavior of the economy in the standard case studied in the literature with CEA. Technically speaking, this case can be seen as a subcase of the ELEA preferences with η constant. The dynamical system under CEA preferences is similar to (14) except that one now has to replace $\eta(H)$ by any η. In this case, under conditions (18)–(20), the economy will reach, in the long run, a BGP. It means that with constant awareness, the accumulation of knowledge, together with environmental maintenance, is sufficient to promote sustainable growth.

This result does not necessarily hold once the positive impact of education on environmental awareness is taken into account. To understand this property, simply refer to the trade-offs governing the agent's decisions. An increase in the effort m_t is a means of improving environmental quality and thus of enhancing welfare. However, it also implies a fall in the nonenvironmental component of welfare because both savings and old age consumption decrease. Consequently, the agent chooses m_t to equate the marginal benefit of maintenance to its marginal cost. Now, other things equal, with accumulation of knowledge the agent pays more attention to the environment. The marginal benefit of maintenance tends to be higher than its marginal cost, giving an incentive to the agent to allocate more resources to maintenance at the expense of savings. This substitution effect is accompanied by an income effect, because more knowledge means more production and more resources to be devoted to savings and maintenance. However, the latter effect does not always offset the former, and economic growth may not be sustained.

The literature on endogenous growth and the environment has defined the necessary conditions on technology, preferences, and environmental dynamics for balanced growth to be possible [for a review of these conditions, refer to Bovenberg and Smulders (1995, 1996), Smulders and Gradus (1996), and Bovenberg and de Mooij 1997)]. In particular, in optimal growth models, the elasticity or environmental awareness η is required to be constant. That is why the papers in this field systematically assume utility functions with constant elasticity. In our setting, there exists an A-BGP, which is economically similar to a BGP, even if this condition does not hold. Indeed, it turns out that this condition can be relaxed by simply requiring environmental awareness to be bounded from above [because $\eta'(H) > 0$], this boundary corresponding to a state of full awareness.

The results summarized in Propositions 1 and 2 clearly challenge the widespread view that human capital accumulation fosters economic growth while being compatible with environmental improvement. If the economy may follow an A-BGP, it may also be caught in a steady state, thereby losing the opportunity to accumulate wealth and to improve environmental quality forever.

An interesting issue is to determine under which conditions the economy may reach one or the other trajectory. A first answer is provided by the analysis of local stability. Denote the share of public expenditures in the education technology by $s(e)$, $s(e) = eg'(e)/g(e)$. Also define as $e^\eta = H\eta'(H)/\eta(H) > 0$ the elasticity of environmental awareness with respect to H.

PROPOSITION 3.

(i) *The asymptotic BGP is locally stable if* $s(\bar{e}) \leq 1/\sigma(\bar{k})$.
(ii) *The steady state is locally stable if* $s(\tilde{e}) \leq 1/\sigma(\tilde{k})$, $(1-\mu)\eta(\tilde{H}) \geq \rho/\gamma$, *and* $\tilde{e}^\eta \in [\underline{\tilde{e}^\eta}, \overline{\tilde{e}^\eta}]$, *with*

$$\underline{\tilde{e}^\eta} = \frac{\Lambda}{(1-\mu)\eta(\tilde{H})s(\tilde{k})s(\tilde{e})} \text{ and } \overline{\tilde{e}^\eta} = \frac{1+\eta(\tilde{H})+\Lambda}{\eta(\tilde{H})s(\tilde{k})s(\tilde{e})}$$

and $\Lambda = [1+\eta(\tilde{H})][1-s(\tilde{k})s(\tilde{e})] - [\frac{\rho}{\gamma}+\mu\eta(\tilde{H})+1][1-\frac{s(\tilde{k})}{\sigma(\tilde{k})}] > 0$.

Proof. See Appendix C. ■

The first stability condition, $s(e) \leq 1/\sigma(k)$, is common to the two solutions. This condition requires the share of public expenditures in education not to be too high.[8] The stability condition $(1-\mu)\eta(\tilde{H}) \geq \rho/\gamma$, for the steady state, is a rewriting of the existence condition (20) for the A-BGP. What is worth mentioning is that stability of the steady state requires another condition to be satisfied and consequently is more difficult to obtain than that of the A-BGP. Actually, the curvature of $\eta(H)$ is crucial for the stability analysis. When $\eta(H)$ is flat, environmental awareness is relatively insensitive to the level of knowledge. The dynamics behaves as if we were in the CEA economy. Thus, there is no room for convergence toward the SS and the economy will be drawn along the A-BGP. In contrast, if environmental awareness exhibits a strong reaction to a change in H, then the accumulation of knowledge substantially affects the dynamics, through this new channel, and may drive the ELEA economy to the SS. The influence of human capital on awareness must be significant; that is, $\eta'(H)$ must be high enough. This is the sense of $\tilde{e}^{\eta} \geq \underline{\tilde{e}^{\eta}}$. Now, at the same time, stability requires the magnitude of the impact of knowledge to be bounded from above ($\tilde{e}^{\eta} \leq \overline{\tilde{e}^{\eta}}$).

4. POLICY ANALYSIS

This section first performs a comparative statics exercise to highlight how both A-BGP and steady state features respond to a modification of the public policy. Next, we turn to the question of whether the public policy can affect the growth prospects of the economy, through its influence on endogenous environmental awareness.[9] From now on, for ease of exposition, the analysis is conducted using specific functional forms:[10]

$$f(k) = Ak^{\alpha}, \alpha \in (0,1), g(e) = e^{1-\beta}, \beta \in (0,1), \text{ and } \eta(H) = \bar{\eta} - \frac{\bar{\eta} - \underline{\eta}}{1+H}. \tag{22}$$

4.1. Comparative Statics

First, we assess the impact of changes in the tax rate and of the level of full awareness $\bar{\eta}$ on the growth rate of the A-BGP.[11] Next, we investigate how a change in the tax rate modifies the steady levels of physical and human capital and of environmental quality. Particular attention will be paid to the role of endogenous environmental awareness.

PROPOSITION 4. *Along the A-BGP,*

(i) *The stronger the concern for the environment, the lower the growth rate.*
(ii) *Increasing the tax enhances economic growth if and only if* $\tau \leq 1 - \alpha$.

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Proof. See Appendix D.1. ■

The impact of environmental awareness on growth differs from the one generally detected in the literature. Gradus and Smulders (1993), Vellinga (1999), and Pautrel (2011) have shown that the long-run growth rate is independent of the degree of environmental concern. In their setting, the negative impact of greener preferences on physical capital accumulation (the polluting input) is exactly offset by the greater incentive to accumulate human capital (the clean input). Here, because education does not rely on agents' decisions (from their point of view, it is exogenous), this compensation does not occur. Stronger awareness implies that agents allocate more resources to environmental maintenance. Consequently, the accumulation of both K and H is slowed.

As far as the impact of the tax rate on growth is concerned, it appears that increasing the tax enhances the growth rate if and only if the tax is initially below the share of human capital in production. This proposition generalizes the standard result of the literature [see Glomm and Ravikumar (1997)] to cases in which the environment is taken into account. An increase in the tax rate has two opposite effects on the agent's income. There is first a direct negative income effect. On one hand, in the first period, the agent has fewer resources to devote to maintenance and savings. On the other, in the second period, she consumes less because the returns on savings decrease. But, at the same time, a higher tax increases the government revenue and stimulates public expenditure on education. More human capital means more production and more income distributed to households. This corresponds to an indirect positive income effect. When $\tau \leq 1-\alpha$, the benefits of a tax increase exceed the costs, and the growth rate of the economy is enhanced.

Let us see how a modification of public policy affects the steady state.

PROPOSITION 5. *In the steady state,*

(i) *Raising the tax increases human capital iff* $\tau < 1-\alpha$.

(ii) *If* $\tau < \min\{1-2\alpha, \hat{\tau}\}$, *with* $\hat{\tau} = \left[\frac{1+\frac{\rho}{\gamma}+\mu\eta}{\alpha(1-\alpha)A^{\frac{1}{\alpha}}}\right]^{\frac{\alpha}{1-\alpha}} < 1-\alpha$, *then a higher tax is also accompanied by higher output and environmental quality.*

Proof. See Appendix D.2. ■

Having $\tau < 1-\alpha$ is again necessary and sufficient for obtaining the result that increasing the share of resources devoted to public education is a means of promoting human capital accumulation. However, this is no longer the case for environmental quality and economic wealth (as measured by output). In other words, $\tau < 1-\alpha$ is necessary but not sufficient to get the *win–win* outcome discussed previously for the A-BGP. Now, any change in the tax rate is accompanied by an additional effect, playing through the endogenous awareness. A higher tax tends to stimulate the accumulation of knowledge. But this, in turn, affects the agent's preferences, which become greener. Consequently, she allocates more resources to maintenance at the expense of savings and physical capital accumulation.

Proposition 5 (ii) displays a sufficient condition under which increasing the tax rate enhances growth of output and environmental quality. Therefore, once the influence of public policy on awareness is taken into account, the comparative statics exercise offers the following conclusion: a political reform can still be globally beneficial to the economy by driving the system to a steady state with higher output and quality. But its success requires the initial tax to be rather low, lower than the usual bound $1 - \alpha$.

4.2. Tax Rate and Growth Pattern: Discussion

We are now coming back to the important question raised by the paper: how does endogenous environmental awareness, as it connects to the public policy, affect growth prospects? In Section 3, a preliminary discussion was conducted in terms of the stability of possible long-run outcomes. Thereafter, we further investigate this issue by putting emphasis on the role of the tax rate.

First of all, it is worth noting that, with the functional forms in (22), there exists a unique locally stable A-BGP for any tax rate $\tau > 0$, as long as condition (20) holds.[12] This means that public policy can have an impact on equilibrium dynamics only by affecting the properties of the steady state. For the example considered in this section, it is easy to show that the tax rate has to be chosen in a particular range (τ_1, τ_2), with $\tau_1 < 1 - \alpha < \tau_2$, in order for the steady state to exist (see Appendix D.2). In the same vein, two of the three stability conditions for the steady state involve the policy instrument.

Suppose that both the A-BGP and the steady state are locally stable. Then one logically expects that for any initial condition (K_0, H_0), with K_0, H_0 not too high, the economy will experience convergence to the steady state. Actually, for any finite and not–too high level of knowledge, the dynamics that prevail is that which drives the economy to the steady state. It is only for a very high level of human capital that a regime switch occurs in the dynamics, when $\eta(H)$ approaches a constant value, making possible asymptotic convergence to the BGP.

So, if the policy maker seeks to reproduce the dynamics of the CEA scenario, with sustained growth, in the ELEA economy, two options exist. One possibility is to choose a tax rate such that the steady state becomes unstable. But then the initial condition crucially matters. Actually, depending on the location of the initial condition with respect to the steady state, the economy may be pushed away from the steady state in the direction of the BGP, which will be approached asymptotically. But rendering the steady state unstable also opens the door to other development patterns, making likely asymptotic convergence to zero.[13] By contrast with this first possibility, the second option reaches its goal for sure. It simply consists in choosing a tax rate outside the range (τ_1, τ_2). In this case, the steady state no longer exists and the economy has no other option but to converge

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to the A-BGP. Note, however, that this option is costly for the economy because the tax rate moves further away from the growth-maximizing rate, $1-\alpha$.

5. CONCLUSION

In this paper, we develop an OLG model with public expenditures on education (financed by an income tax) and the environment. Our purpose is to assess a new channel through which education and the accumulation of knowledge may influence economic and environmental dynamics: environmental awareness.

The literature on growth and the environment generally assumes that awareness is constant and obtains that the economy achieves a BGP in the long run that is sustainable, provided agents engage in environmental maintenance. Relaxing this assumption leads to different conclusions. In the case of education-led environmental awareness, the intertemporal competitive equilibrium features are modified. In contrast with the previous case, balanced growth is no longer the rule. Indeed, with the accumulation of knowledge, awareness increases and agents progressively divert themselves from polluting but productive activities. This evolution in tastes benefits the environment, because agents get higher incentives to engage in green activities. As a result, the economy may either reach a steady state or approach an A-BGP in the long run. The convergence toward one or the other equilibrium is dictated by the sensitivity of environmental awareness knowledge.

An analysis of the impact of education policy on growth and the environment is also conducted. Again, the role played by endogenous awareness is highlighted. In particular, the critical level of taxation that determines whether, by raising the tax, the economy may experience higher growth and better environmental quality is lowered when awareness is endogenous. In addition, the policy maker, whose purpose is to maintain a positive growth rate for the economy in the long run, can avoid convergence to the steady state—that can be seen as a limit to growth [Stokey (1998)]—by appropriately choosing the tax rate.

NOTES

1. This survey was conducted on 20,000 citizens in the 25 member states. See EC (2005). It was updated in EC (2008).

2. The survey also shows that increasing environmental awareness is considered to be as effective as stringer regulation and better enforcement at solving environmental problems.

3. See notably Bovenberg and Smulders (1995, 1996), Smulders and Gradus (1996), and Bovenberg and de Mooij (1997).

4. This property holds for the cases of logarithmic and Cobb–Douglas utility functions [Zhang (1999)].

5. As an illustration of ELEA preferences, one may consider a log-additive utility function: $U(c_{t+1}, Q_{t+1}, H_{t+1}) = \log c_{t+1} + \eta(H_{t+1}) \log Q_{t+1}$.

6. The case where the non-negativity constraint on m_t is binding is not addressed. The dynamical system under zero maintenance features environmental quality degradation. Even if current generations do not abate pollution, there exists a future date when generations will find it worthwhile to maintain the environment. Thus, the economy cannot end up in the regime with zero maintenance. Because we

are interested in long-run issues, the analysis concentrates on the interior solution. When required, the particular features of the CEA case will be emphasized.

7. Maintenance must be non-negative along the A-BGP; this requires

$$\frac{(1-\tau)[f(\bar{k})-\bar{k}f'(\bar{k})]}{\bar{k}} \geq g[\tau f(\bar{k})]$$

with $\bar{k}$ being the long-run ratio of physical to human capital along the A-BGP.

8. Because, by definition, $s(e) < 1$, it holds for the Cobb–Douglas and the CES with $\phi \geq 0$ and for some $\phi < 0$ not too close to -1.

9. Thus, the policy analysis does not adopt a normative approach. Rather, it is very much along the line of Prieur et al. (2011), who assess the impact of environmental policy on growth and the environment in a framework very similar to ours.

10. Technologies are those used by Glomm and Ravikumar (1997). In addition, $\eta(H)$ is defined consistently with Assumption 3.

11. Note that the comparative statics exercise would be strictly identical if one were to consider the CEA case for any given η.

12. In other words, all existence and stability conditions—other than (20)—are satisfied regardless of the level of the tax rate. This is also a feature of the CEA scenario.

13. Roughly speaking, in the (H, K) plan, starting from the right of the unstable steady state is consistent with convergence to the A-BGP. However, starting from the left of the steady state, the economy may be caught in a poverty trap with human and physical capital (and environmental quality) diminishing from period to period.

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APPENDIX A: EXISTENCE OF AN A-BGP (PROPOSITION 1)

We are interested in cases where aggregate variables grow at non-negative, nonconstant rates. The growth factor satisfies $\chi_i \geq 1$ for $i = K_t, H_t, Q_t$. The dynamics is

$$\begin{cases} Q_{t+1} = \gamma\eta(H_{t+1})H_{t+1}k_{t+1} & (*), \\ H_{t+1} = H_t g[\tau f(k_t)] & (+), \\ Q_{t+1} = (1-\mu)Q_t - \rho H_t k_t + \gamma\left\{(1-\tau)H_t[f(k_t) - k_t f'(k_t)] - H_{t+1}k_{t+1}.\right\} & (\times). \end{cases}$$

Substitute $(*)$ into $(\times)$:

$$\left[1 + \frac{1}{\eta(H_{t+1})}\right]\frac{Q_{t+1}}{Q_t} = 1 - \mu - \frac{\rho}{\gamma\eta(H_t)} + \frac{(1-\tau)}{\eta(H_t)}\left[\frac{f(k_t)}{k_t} - f'(k_t)\right]. \qquad \textbf{(A.1)}$$

• Assume first that $\lim_{t\to+\infty} k_t = 0 \leftrightarrow \lim_{t\to+\infty} K_t \ll \lim_{t\to+\infty} H_t$:
From $(+)$ and $g(0) = f(0) = 0$, $\lim_{t\to+\infty} \chi_{H_t} = 0$, which contradicts the condition $\chi_i \geq 1$ for all i.

• Assume next that $\lim_{t\to+\infty} k_t = +\infty \leftrightarrow \lim_{t\to+\infty} K_t \gg \lim_{t\to+\infty} H_t$:
At least asymptotically, we have $\chi_{K_t} > \chi_{H_t}$: $\lim_{t\to+\infty} \chi_{K_t} > \lim_{t\to+\infty} \chi_{H_t}$.

From $(+)$, $\lim_{k\to+\infty} f(k) = +\infty$, and $\lim_{e\to+\infty} g(e) = +\infty$, it turns out that $\lim_{t\to+\infty} \chi_{H_t} = g[\tau f(\lim_{t\to+\infty} k_t)] = +\infty$. Thus, $\lim_{t\to+\infty} H_t = +\infty$ and, from Assumption 4, $\lim_{t\to+\infty} \eta(H_t) = \bar{\eta}$.

Together with $(*)$, $\lim_{t\to+\infty} Q_{t+1}/K_{t+1} = \gamma\bar{\eta}$. Therefore, $\lim_{t\to+\infty} \chi_{K_t} = \lim_{t\to+\infty} \chi_{Q_t}$.

But, according to (A.1),

$$\lim_{t\to+\infty}\chi_{Q_t}=\lim_{t\to+\infty}\frac{1-\mu-\frac{\rho}{\gamma\eta(H_t)}+\frac{(1-\tau)}{\eta(H_t)}\left[\frac{f(k_t)}{k_t}-f'(k_t)\right]}{1+\frac{1}{\eta(H_{t+1})}}.$$

Under Assumption 1, because $\lim_{t\to+\infty} f(k_t)/k_t = \lim_{k_t\to+\infty} f(k_t)/k_t$ when $\lim_{t\to+\infty} k_t = +\infty$, we obtain

$$\lim_{t\to+\infty}\chi_{Q_t}=\frac{1-\mu-\frac{\rho}{\gamma\bar{\eta}}}{1+\frac{1}{\bar{\eta}}}<+\infty;$$

thus $\lim_{t\to+\infty}\chi_{K_t} = \lim_{t\to+\infty}\chi_{Q_t} < +\infty = \lim_{t\to+\infty}\chi_{H_t}$. There is a contradiction.

$\Rightarrow$ The only possibility is $\lim_{t\to+\infty} k_t = k$, with $0 < k < \infty$, which implies that $\lim_{t\to+\infty}\chi_{K_t} = \lim_{t\to+\infty}\chi_{H_t}$. From (+), $\lim_{t\to+\infty}\chi_{H_t} = g[\tau f(k)]$. If $g(\tau f(k)) \geq 1$, then $\lim_{t\to+\infty}\eta(H_t) = \bar{\eta}$. From (∗), $\lim_{t\to+\infty} Q_{t+1}/K_{t+1} = \gamma\bar{\eta}$. Therefore, $\lim_{t\to+\infty}\chi_{K_t} = \lim_{t\to+\infty}\chi_{Q_t} = \lim_{t\to+\infty}\chi_{H_t}$. Now, from (A.1), we obtain

$$\underbrace{\gamma(1+\bar{\eta})g[\tau f(k)]}_{I(k)}=\underbrace{\gamma(1-\tau)\frac{f(k)-kf'(k)}{k}+\gamma\bar{\eta}(1-\mu)-\rho}_{J(k)}. \quad \textbf{(A.2)}$$

This equation is exactly the one obtained from evaluating the dynamical system of the CEA case along a BGP. Proving the existence of an A-BGP boils down to showing that there exists an intersection $\bar{k}$ between $I(k)$ and $J(k)$.

From Assumptions 1 and 2, $I(k)$ is increasing and concave. Moreover, $I(0) = 0$ and $\lim_{k\to+\infty} I(k) = +\infty$.

The first derivative of $J(k)$ is

$$J'(k)=\gamma(1-\tau)\frac{f''(k)}{s(k)}\left[\sigma(k)-s(k)\right];$$

therefore, $J'(k) \leq 0 \Leftrightarrow \sigma(k) \geq s(k)$. Because there exists an upper bound on the attainable capital, we necessarily have $\lim_{k\to+\infty}\frac{f(k)-kf'(k)}{k} = 0 \Leftrightarrow \lim_{k\to+\infty} J(k) = \gamma\bar{\eta}(1-\mu)-\rho \lesseqgtr 0$. Assume that $\gamma\bar{\eta}(1-\mu)-\rho > 0$; then $\gamma[1+\bar{\eta}(1-\mu)] \geq \rho$ and

$$\lim_{k\to 0}\frac{f(k)-kf'(k)}{k}>\frac{1}{1-\tau}. \quad \textbf{(A.3)}$$

Therefore $0 < \lim_{k\to 0} J(k) < \infty$.

There exists a unique intersection $\bar{k}$ between the two functions. Because $H_{t+1}/H_t = g[\tau f(\bar{k})]$, the unique constant growth rate is $\theta = g[\tau f(\bar{k})] - 1$.

APPENDIX B: EXISTENCE OF A STEADY STATE (PROPOSITION 2)

A steady state solves

$$\begin{cases} Q = \gamma\eta(H)Hk, \\ \mu Q = \{\gamma[(1-\tau)(f(k)-kf'(k))-k]-\rho k\}\, H, \\ g[\tau f(k)] = 1. \end{cases} \quad \textbf{(B.1)}$$

The last equation in (B.1) gives the equilibrium ratio between K and H,

$$\tilde{k}(\tau) = f^{-1}\left[\frac{g^{-1}(1)}{\tau}\right], \quad \textbf{(B.2)}$$

and combining the two first equations yields

$$\mu\eta(\tilde{H}) = (1-\tau)\frac{f(\tilde{k})-\tilde{k}f'(\tilde{k})}{\tilde{k}} - \frac{\rho}{\gamma} - 1. \quad \textbf{(B.3)}$$

Under Assumption 3, this solution has a unique solution iff

$$(1-\tau)\frac{f(\tilde{k})-\tilde{k}f'(\tilde{k})}{\tilde{k}} \in \left(\mu\underline{\eta}+1+\frac{\rho}{\gamma}, \mu\bar{\eta}+1+\frac{\rho}{\gamma}\right),$$

the steady state level of human capital being given by

$$\tilde{H}(\tau) = \eta^{-1}\left\{\frac{1}{\mu\gamma}\left[\gamma(1-\tau)\frac{f(\tilde{k}(\tau))-\tilde{k}(\tau)f'(\tilde{k}(\tau))}{\tilde{k}(\tau)} - \gamma - \rho\right]\right\}.$$

Finally, we obtain $\tilde{K}(\tau) = \tilde{k}(\tau)\tilde{H}(\tau)$ and $\tilde{Q}(\tau) = \gamma\eta[\tilde{H}(\tau)]\tilde{K}(\tau)$.

APPENDIX C: LOCAL STABILITY OF LONG RUN EQUILIBRIA (PROPOSITION 3)

C.1. LOCAL STABILITY OF THE A-BGP

The dynamics characterizing the A-BGP is obtained by replacing $\eta(H_{t+1})$ with $\bar{\eta}$ in (14):

$$\begin{cases} q_{t+1} = \gamma\bar{\eta}k_{t+1}, \\ \chi(k_t)q_{t+1} = (1-\mu)q_t - \rho k_t + \gamma(1-\tau)w(k_t) - \gamma\chi(k_t)k_{t+1}, \end{cases}$$

with $q_t = Q_t/H_t$ and $\chi(k_t) = g[\tau f(k_t)]$. By linearizing this dynamics around the steady state $(\bar{k}, \bar{q})$ and making use of (A.2) in Appendix A, the system reduces to one-dimensional

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dynamics:

$$dq_{t+1} = \psi dq_t \text{ with } \psi = \frac{\bar{\eta}(1-\mu) - \frac{\rho}{\gamma}}{(1+\bar{\eta})\chi(\bar{k})}\left[1 - \frac{s(\bar{k})}{\sigma(\bar{k})}\right] + \frac{s(\bar{k})}{\sigma(\bar{k})} - s(\bar{k})s(\bar{e}).$$

Under condition (19), $s(\bar{k})/\sigma(\bar{k}) < 1$. Now assume that $s(\bar{e}) < 1/\sigma(\bar{k})$ (because $s(\bar{e}) < 1$, it holds for the Cobb–Douglas, for the CES with $\phi \geq 0$, and for some $\phi < 0$ not too close to -1). This condition, together with (19) and (20), implies $\psi > 0$. Local stability then imposes $\psi < 1$, which is equivalent to $[\bar{\eta}(1-\mu) - \rho/\gamma - (1+\bar{\eta})\chi(\bar{k})][1 - s(\bar{k})/\sigma(\bar{k})] < (1+\bar{\eta})\chi(\bar{k})s(\bar{k})s(\bar{e})$. According to (A.2), this inequality is satisfied because the left-hand side is negative.

To summarize, if $s(\bar{e}) < 1/\sigma(\bar{k})$, then the A-BGP is locally stable.

C.2. LOCAL STABILITY OF THE STEADY STATE

Consider the dynamical system (14). From the first equation, environmental quality is positively linked to human and physical capital in every period, which means that this system reduces to two-dimensional dynamics. Linearizing the resulting system in (H, k) around the steady state $(\tilde{H}, \tilde{k})$, and making use of (21) yield

$$\begin{cases} dH_{t+1} = dH_t + \frac{\tilde{H}}{\tilde{k}}s(\tilde{k})s(\tilde{e})dk_t, \\ dk_{t+1} = \frac{1}{1+\eta(\tilde{H})}\left[-\mu\eta(\tilde{H})\tilde{e}^{\eta}\frac{\tilde{k}}{\tilde{H}}dH_t + Ydk_t\right], \end{cases}$$

with $\tilde{e}^{\eta} = \tilde{H}\eta'(\tilde{H})/\eta(\tilde{H})$ and $Y = [1+\eta(\tilde{H}][1 - s(\tilde{k})s(\tilde{e})] - [1 - \frac{s(\tilde{k})}{\sigma(\tilde{k})}](1-\tau)w(k)/k - \eta(\tilde{H})\tilde{e}^{\eta}s(\tilde{k})s(\tilde{e})$.

Using the definition of k_t, $k_t = K_t/H_t$, one finally gets the linearized system in (dH, dK):

$$\begin{cases} dH_{t+1} = \left[1 - s(\tilde{k})s(\tilde{e})\right]dH_t + \frac{s(\tilde{k})s(\tilde{e})}{\tilde{k}}dK_t \\ dK_{t+1} = \tilde{k}\left[1 - s(\tilde{k})s(\tilde{e}) - \frac{\Lambda-(1-\mu)\eta(\tilde{H})\tilde{e}^{\eta}s(\tilde{k})s(\tilde{e})}{1+\eta(\tilde{H})}\right]dH_t + \left[s(\tilde{k})s(\tilde{e}) + \frac{\Lambda-\eta(\tilde{H})\tilde{e}^{\eta}s(\tilde{k})s(\tilde{e})}{1+\eta(\tilde{H})}\right]dK_t \end{cases}$$

with $\Lambda = [1+\eta(\tilde{H})][1 - s(\tilde{k})s(\tilde{e})] - [\rho/\gamma + \mu\eta(\tilde{H}) + 1][1 - s(\tilde{k})/\sigma(\tilde{k})] > 0$ under $s(\tilde{e}) < 1/\sigma(\tilde{k})$ and $(1-\mu)\eta(\tilde{H}) \geq \frac{\rho}{\gamma}$ (rewriting of (20)). The characteristic polynomial is

$$P(\lambda) = \lambda^2 - \left[1 + \frac{\Lambda - \eta(\tilde{H})\tilde{e}^{\eta}s(\tilde{k})s(\tilde{e})}{1+\eta(\tilde{H})}\right]\lambda + \frac{\Lambda - (1-\mu)\eta(\tilde{H})\tilde{e}^{\eta}s(\tilde{k})s(\tilde{e})}{1+\eta(\tilde{H})}.$$

Note that what is changing now, with regard to Appendix C.1, is the role played by education, through its influence on EA. Let us calculate values of $P(\lambda)$ at critical bounds 0, 1, and -1:

$$P(1) = \frac{\mu\eta(\tilde{H})\tilde{e}^{\eta}s(\tilde{k})s(\tilde{e})}{1+\eta(\tilde{H})} > 0; P(-1) = 2\left[1 + \frac{\Lambda - \eta(\tilde{H})\tilde{e}^{\eta}s(\tilde{k})s(\tilde{e})}{1+\eta(\tilde{H})}\right] + P(1);$$

and $P(0)$ is the constant term of the characteristic polynomial.

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There exists a nonempty range $[\underline{\tilde{e}^{\eta}}, \overline{\tilde{e}^{\eta}}]$ (as long as $\mu < 0,5$) with

$$\underline{\tilde{e}^{\eta}} = \frac{\Lambda}{(1-\mu)\eta(\tilde{H})s(\tilde{k})s(\tilde{e})} \text{ and } \overline{\tilde{e}^{\eta}} = \frac{1+\eta(\tilde{H})+\Lambda}{\eta(\tilde{H})s(\tilde{k})s(\tilde{e})},$$

such that for any EA's elasticity to education belonging to this range, the steady state is locally stable. Indeed, in this case, we have $P(-1) > 0$ and $P(0) < 0$, which means that the two roots of $P(\lambda)$ belongs to $]-1, 1[$ and have opposite signs. Convergence is oscillatory.

To summarize, if $s(\tilde{e}) < 1/\sigma(\tilde{k})$, $(1-\mu)\eta(\tilde{H}) \geq \rho/\gamma$, and $\tilde{e}^{\eta} \in [\underline{\tilde{e}^{\eta}}, \overline{\tilde{e}^{\eta}}]$, then the steady state is locally stable.

APPENDIX D: COMPARATIVE STATICS

D.1. COMPARATIVE STATICS: A-BGP (PROPOSITION 4)

Along the A-BGP, from (14), the system to be analyzed reduces to

$$\begin{cases} \chi = g[\tau f(\bar{k})], \\ (1+\bar{\eta})g[\tau f(\bar{k})] = \bar{\eta}(1-\mu) - \frac{\rho}{\gamma} + (1-\tau)\left(\frac{w(\bar{k})}{\bar{k}}\right), \end{cases} \tag{D.1}$$

where $\chi = \chi(\bar{k})$ is the growth factor common to all the state variables: $\chi = K_{t+1}/K_t = H_{t+1}/H_t = Q_{t+1}/Q_t$.

Total differentiation of the equations in (D.1) yields

$$\begin{cases} d\chi = g'[\tau f(\bar{k})][f(\bar{k})d\tau + \tau f'(\bar{k})dk], \\ (1+\eta)d\chi + \chi d\bar{\eta} = (1-\mu)d\bar{\eta} + (1-\tau)\left[\frac{w(\bar{k})}{\bar{k}}\right]' dk - \left(\frac{w(\bar{k})}{\bar{k}}\right) d\tau. \end{cases} \tag{D.2}$$

Assume first that $d\bar{\eta} = 0$ and manipulate these two equations to obtain

$$\left\{1 + \bar{\eta} - \frac{(1-\tau)\left[\frac{w(\bar{k})}{\bar{k}}\right]'}{g'[\tau f(\bar{k})]\tau f'(\bar{k})}\right\} \frac{d\chi}{d\tau} = -\frac{f(\bar{k})f''(\bar{k})}{f'(\bar{k})}\left\{-\sigma(\bar{k}) + \frac{(1-\tau)[\sigma(\bar{k}) - s(\bar{k})]}{\tau s(\bar{k})}\right\}.$$

The coefficient on the LHS is positive under condition (19). Direct calculation then reveals that

$$\frac{d\chi}{d\tau} \geq 0 \leftrightarrow \tau \leq \bar{\varphi} \text{ with } \bar{\varphi} = \frac{\sigma(\bar{k}) - s(\bar{k})}{\sigma(\bar{k})s(\bar{k}) + \sigma(\bar{k}) - s(\bar{k})}.$$

Note that for the Cobb–Douglas technology ($y = Ak^{\alpha}$), $\sigma = 1$ and $s = 1 - \alpha$; thus the condition simply reads $\tau \leq 1 - \alpha$. With a CES technology, $s(k)$ is no longer constant, which implies that $\bar{\varphi}$ depends on τ through $\bar{k}$. But the result is qualitatively unchanged because we can easily check that there exists a critical value $\bar{\tau}$ such that for any $\tau \leq \bar{\tau}$, $d\chi/d\tau \geq 0$.

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Next suppose that $d\tau = 0$. The same computations yield

$$\left\{1 + \bar{\eta} - \frac{(1-\tau)\left[\frac{w(\bar{k})}{\bar{k}}\right]'}{g'[\tau f(\bar{k})]\tau f'(\bar{k})}\right\}\frac{d\chi}{d\bar{\eta}} = 1 - \mu - \chi.$$

Thus

$$\frac{d\chi}{d\bar{\eta}} \leq 0 \leftrightarrow \chi \geq 1 - \mu.$$

D.2. COMPARATIVE STATICS: STEADY STATE (PROPOSITION 5)

With the functional forms of Section 4, we obtain the steady state value of k: $\tilde{k}(\tau) = (A\tau)^{-\frac{1}{\alpha}}$, with $\tilde{k}'(\tau) < 0$ and

$$\tilde{H} = \tilde{H}(\tau) = \frac{(1-\tau)(1-\alpha)A^{\frac{1}{\alpha}}\tau^{\frac{1-\alpha}{\alpha}} - (1 + \frac{\rho}{\gamma} + \mu\underline{\eta})}{1 + \frac{\rho}{\gamma} + \mu\bar{\eta} - (1-\tau)(1-\alpha)A^{\frac{1}{\alpha}}\tau^{\frac{1-\alpha}{\alpha}}},$$

this expression being positive under condition (21).

The first derivative of $\tilde{H}(\tau)$ is

$$\tilde{H}'(\tau) = \frac{(1-\alpha)A^{\frac{1}{\alpha}}(1-\alpha-\tau)\tau^{\frac{1-\alpha}{\alpha}-1}\mu(\bar{\eta} - \underline{\eta})}{\alpha[1 + \frac{\rho}{\gamma} + \mu\bar{\eta} - (1-\tau)(1-\alpha)A^{\frac{1}{\alpha}}\tau^{\frac{1-\alpha}{\alpha}}]^2}.$$

Because $\tilde{H}$ reaches its maximum at $\tau = 1 - \alpha$, for condition (21) to hold, it is necessary that $\tilde{H}(1-\alpha) > 0 \Leftrightarrow \alpha[A(1-\alpha)]^{\frac{1}{\alpha}} \in (1 + \rho/\gamma + \mu\underline{\eta}, 1 + \rho/\gamma + \mu\bar{\eta})$. Thus, there exists a nonempty range (τ_1, τ_2), with $\tau_1 < 1 - \alpha < \tau_2$, τ_1, τ_2 being the solutions to $(1-\tau)(1-\alpha)A^{\frac{1}{\alpha}}\tau^{\frac{1-\alpha}{\alpha}} = (1 + \frac{\rho}{\gamma} + \mu\underline{\eta})$, such that for any tax rate chosen in this range, $\tilde{H}$ is uniquely defined.

Direct calculations yield the value of environmental quality in the long run:

$$\tilde{Q} = \tilde{Q}(\tau) = \gamma[\bar{\eta}\tilde{H}(\tau) + \underline{\eta}]\frac{\tilde{H}(\tau)\tilde{k}(\tau)}{1 + \tilde{H}(\tau)}.$$

The first term between brackets is increasing in τ as long as $\tau \leq 1 - \alpha$. The second term can be rewritten as

$$\frac{\tilde{H}(\tau)\tilde{k}(\tau)}{1 + \tilde{H}(\tau)} = \frac{(1-\alpha)(1-\tau)\tau^{-1} - (1 + \frac{\rho}{\gamma} + \mu\underline{\eta})A^{-\frac{1}{\alpha}}\tau^{-\frac{1}{\alpha}}}{\mu(\bar{\eta} - \underline{\eta})}$$

and one can easily check that this term is also increasing in τ iff $\tau < \hat{\tau}$ with $\hat{\tau} = [\frac{1 + \frac{\rho}{\gamma} + \mu\underline{\eta}}{\alpha(1-\alpha)A^{\frac{1}{\alpha}}}]^{\frac{\alpha}{1-\alpha}} \in (\tau_1, 1 - \alpha)$.

In sum, when $\tau < \hat{\tau}$, an increase in the tax rate translates into an increase in environmental quality.

Finally, it remains to examine how output responds to changes in the tax rate. Noticing that $\tilde{Y}(\tau) = \tilde{H}(\tau)/\tau$, one obtains $\tilde{Y}'(\tau) > 0 \Leftrightarrow \tilde{H}'(\tau)\tau - \tilde{H}(\tau) > 0$. Let us compute the second-order derivative of $\tilde{H}$:

$$\tilde{H}''(\tau) = \frac{(1-\alpha)^2 A^{\frac{1}{\alpha}} \mu(\bar{\eta}-\underline{\eta})\tau^{\frac{1-3\alpha}{\alpha}} \left\{(1-2\alpha-\tau)[1+\frac{\rho}{\gamma}+\mu\bar{\eta}-(1-\tau)(1-\alpha)A^{\frac{1}{\alpha}}\tau^{\frac{1-\alpha}{\alpha}}]+2A^{\frac{1}{\alpha}}(1-\alpha-\tau)^2\tau^{\frac{1-\alpha}{\alpha}}\right\}}{\alpha[1+\frac{\rho}{\gamma}+\mu\bar{\eta}-(1-\tau)(1-\alpha)A^{\frac{1}{\alpha}}\tau^{\frac{1-\alpha}{\alpha}}]^3}.$$

Thus when $\tau \leq 1-2\alpha$, $\tilde{H}$ is strictly convex. Suppose that $\tau_1 < 1-2\alpha$. Then the strictly increasing and convex $\tilde{H}$ on $[\tau_1, 1-2\alpha]$, with $\tilde{H}(\tau_1) = 0$, satisfies $\tilde{H}'(\tau)\tau - \tilde{H}(\tau) > 0$. Thus, $\tilde{Y}'(\tau) > 0$ for any $\tau \in [\tau_1, 1-2\alpha]$.