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Time-separable Utility, Leisure and Human Capital Accumulation: What New Implications for the Environment-Growth Nexus?

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Summary

Using a time-separable utility function where leisure is introduced through the disutility of working time and is adjusted for quality, as measured by human capital to capture home production, we demonstrate that the environmental policy is harmful for growth. A tighter environmental tax reduces the incentives to educate by increasing leisure time and lowers the steady-state growth rate and lifetime welfare, whatever the source of pollution. We also demonstrate that the intertemporal elasticity of substitution in labor supply plays a crucial role in the marginal impact of the environmental tax on growth and welfare. When the positive influence of human capital is added into preferences (by explicitly modelling the home production sector), we find that the environmental policy promotes steady-state growth. This result challenges the finding by Hettich (1998) according to which, in the presence of leisure, the environmental tax does not affect human capital accumulation if the source of pollution is output.

Keywords: Leisure, Human Capital, Environmental Tax

JEL Classification: C, Q56

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Time-separable utility, leisure and human capital accumulation: What new implications for the environment-growth nexus?

Xavier Pautrel[*][†]

Abstract

Using a time-separable utility function where leisure is introduced through the disutility of working time and is adjusted for *quality*, as measured by human capital to capture home-production, we demonstrate that the environmental policy is harmful for growth. A tighter environmental tax reduces the incentives to educate by increasing leisure time and lowers the steady-state growth rate and lifetime welfare, whatever the source of pollution. We also demonstrate that the intertemporal elasticity of substitution in labor supply plays a crucial role in the marginal impact of the environmental tax on growth and welfare.

When the positive influence of human capital is added into preferences (by explicitly modelling the home production sector), we find that the environmental policy promotes steady-state growth. This result challenges the finding by Hettich (1998) according to which, in the presence of leisure, the environmental tax does not affect human capital accumulation if the source of pollution is output.

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1 Introduction

Is it possible to obtain both an improving environment and a higher economic growth when the channel of transmission is education? In the current knowledge- and education-based industrialized economies, it appears as an important questioning which have received a positive answer from recent and older contributions. The aim of this article is to re-investigate this question emphasizing leisure and home production.

While the link between the environment and growth has already been extendedly investigated (see Xepapadeas, 2005; Brock and Taylor, 2005, for example), especially when learning-by-doing and innovation are the engines of growth, fewer works study this link when human capital accumulation is the source of growth. In a seminal contribution, Gradus and Smulders (1993) demonstrate that the environment influences growth in a Lucas (1988)'s framework only when pollution is assumed to directly affect human capital accumulation.[1] Nevertheless, Hettich (1998) obtains a positive influence of the environmental policy tax on growth by introducing elastic labor supply, when pollution arises from the physical capital stock. In such a case, a tighter environmental tax compels firms to increase their abatement activities at the expense of the household's consumption. To counteract this negative effect, households substitute leisure to education and the growth rate rises.[2] More recently, Grimaud and Tournemaine (2007) demonstrate that a higher environmental tax promotes growth, in a model combining R&D and human capital accumulation, where education directly enters the utility function as a consumption good and knowledge from R&D reduces the flow of pollution emissions. By increasing the price of the good whose production pollutes the higher tax rate reduces the relative cost of education and therefore incites agents to invest in human capital accumulation. Because education is the engine of growth, the steady-state rate of growth rises.

These two works highlight how preferences are important in the link between environment and growth when the channel of transmission is education. The present article contributes to this field by considering that the level of human capital affects the disutility of non-leisure activities and modifies the returns to educational activities. This idea originates from Becker (1965) and

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[1] To find a positive influence of the environment on growth in the Lucas (1988)'s framework, Gradus and Smulders assume that pollution depreciates the stock of human capital. In the same vein van Ewijk and van Wijnbergen (1995) consider that pollution reduces the ability to train. Pautrel (2008) demonstrates that a positive effect may be found with a human capital accumulation à la Lucas (1988) when the detrimental impact of pollution on life expectancy is taken into account.

[2] However, Hettich demonstrates that the link between the environment and growth does no longer exist when pollution originates from final output rather than physical capital. By taxing output, a tighter environmental policy reduces both the returns to physical capital and the wage rate which contributes to the returns to education. The incentives of agents to invest more in education vanish.

Heckman (1976) who consider that human capital has nonmarket benefits. As shown by Benhabib et al. (1991) it is related to models incorporating home production and has been used in the study of business cycle theory and in other macro-economic modelling by Greenwood et al. (1988), Collard (1999); Cassou and Lansing (1998, 2006); Hercowitz and Sampson (1991); Blackburn and Varvarigos (2008), amongst others. As noted by Blackburn and Varvarigos (2008) "*Under such circumstances, an increase in human capital causes not only an increase in the productivity of non-leisure occupations (working and learning), but also an increase in the marginal disutility (or opportunity cost) of these occupations (because of the increase in productivity in home activities).*" Following the aforementioned literature, we model preferences as a time-separable utility function including human capital-adjusted leisure.

The contribution of this article is twofold. First, it demonstrates that a tighter environmental tax is harmful to growth in a model with human capital accumulation à la Lucas (1988), when preferences are time-separable and leisure enters utility through the disutility of working time adjusted by human capital. Indeed, in such a framework, working-time increases with the current wage rate and it is not affected by consumption due to the time-separability of preferences. Furthermore, the returns to education are positively influenced by working-time because the negative impact of working-time in preferences is adjusted by human capital. As a result, by reducing the wage rate, a tighter environmental tax leads agents to diminish their working-time. The returns to education fall and agents decide to invest less in human capital accumulation. The environmental policy is detrimental for growth.

The intertemporal elasticity of substitution in labor supply plays a crucial role in that result. When it tends to infinity and when it tends to 0, the environmental taxation does not impact the steady-state rate of growth. Indeed, in the first case, the the returns to education only depends on the productivity of education like in Hettich (1998). In the second case, labor supply is inelastic and the framework is similar to Gradus and Smulders (1993). Performing a numerical application, we show that, for intermediate values of the intertemporal elasticity of substitution in labor supply, the detrimental impact of the environmental tax on growth increases in the intertemporal elasticity of substitution in labor supply, for the chosen parameter values. We also show that a tighter environmental tax reduces the individual steady-state welfare, except when the intertemporal elasticity of substitution in labor supply is low[3] or green preferences are high enough.

Our second contribution is to demonstrate that when the positive influence of human capital

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[3] What is empirically relevant. See among other Evers et al. (2008).

is added into preferences (by modelling explicitly the home production sector), the environmental taxation promotes human capital accumulation. Indeed, the returns to education integrate now the positive influence of human capital in utility that offsets the negative impact of working-time disutility. Thus, we show that in a model with human capital accumulation à la Lucas (1988), even if the output is the source of pollution, the environmental policy enhances growth when leisure is introduced into utility under the condition that leisure is adjusted by human capital. That result challenges the finding by Hettich (1998) according to which, in the presence of leisure, the environmental tax does not affect human capital accumulation if the source of pollution is output.

This article is build as follows. In section 2, the model is exposed. In section 3, the expression of the steady-state growth rate in the economy is derived. In section 4, the impact of the environmental tax on growth according to different assumptions about the utility function and the mechanisms underlying the results are enonced and the impact of the environmental tax in terms of individual welfare is examined. Section 5 concludes.

2 The model

Time is continuous. The economy is populated by many, identical, infinitely lived individuals. Population is constant and his size is normalized to unity. Firms operate in a competitive environment. There exists a government that implements the environmental policy by taxing the emissions of pollutants at a rate $\tau \in]0,1[$ and by using tax revenues to finance abatement activities that it publicly provides to curb pollution.

2.1 The household's decisions

Given a total time endowment normalized to one, households allocate their time across three activities: they supply labor effort to firms in the amount u, devote time to human capital formation (learning) in the amount e , and spend the remainder of their time $1-u-e$ in leisure. Consequently, following Lucas (1988), the household's stock of human capital h evolves as

$$\dot{h}(t) = A_h e(t) h(t) \tag{1}$$

where $\dot{h}(t) \equiv dh(t)/dt$ and A_h is the efficiency in learning activities.

To clarify the exposition, we assume that the representative household has preferences linked to environmental concerns (called "*environmental*" preferences) and preferences independent from the environment (called "*non-environmental*" preferences). Instantaneous "*non-environmental*" utility are defined as:

$$u_{NE}(t) = \log[c(t) + h(t)\mathcal{V}(e(t) + u(t))], \qquad \text{with } \mathcal{V}'(\cdot) < 0,\ \mathcal{V}''(\cdot) < 0 \tag{2}$$

where c is private consumption, $u + e$ is time devoted to non-leisure activities (working time, production and education). The function $\mathcal{V}(\cdot) > 0$ captures the negative impact of non-leisure time on utility. The form of the utility function implies that the marginal rate of substitution between consumption and labour is independent of the level of consumption. It means that the amount of labour is independent from intertemporal consumption decisions. The term $h\mathcal{V}(\cdot)$ captures the idea, originated from Becker (1965) and Heckman (1976) that an increases in human capital causes not only an increase in the productivity of non-leisure activities (production and education) but also an increase in the opportunity-cost of these activities or similarly an increase in the productivity of the input of time used in home production. In such perspective, "*leisure is not valued for is own sake, but for what can be done with it*" (Campbell and Ludvigson, 2001). As noted in the introduction, such a time-separable preferences integrating home production have been extensively used in macro-economic modelling and especially in real business cycle theory.

Following Hercowitz and Sampson (1991), we specify the function $\mathcal{V}(\cdot)$ in two alternative ways, called respectively (for the ease of the exposition) a "*disutility of quality-adjusted forgone leisure*" specification and a "*utility of quality-adjusted leisure*" specification:

$$\mathcal{V}(u + e) = -B(u + e)^{1+\gamma}, \tag{3}$$

$$\mathcal{V}(u + e) = B(1 - (u + e)^{1+\gamma}), \tag{4}$$

with $\gamma > 0$ and $B > 0$.

In the first specification (equation 3), the term $h\mathcal{V}(\cdot)$ represents a quality-adjusted measure of the disutility of forgone leisure and may be viewed as a reduced form of a specification that incorporates home production (see Benhabib et al., 1991). It integrates the amount of human capital h to take into account the fact that leisure serves as an input to home production activities and its efficiency is enhanced by human capital. As noted by Blackburn and Varvarigos (2008), the linearity in h is assumed to obtain stationnary time-allocations along the balanced growth path. The parameter $1 + \gamma$ influences the disutility of total effort spent in non-leisure activities and the ratio $1/\gamma$ measures the elasticity of effort spent on each activity with respect to the returns to working. The assumption that $\gamma > 0$ (that is convexity) is justified by Hercowitz and Sampson (1991) as a fatigue effect.[4] Such a form has been used extensively used in RBC literature (by Hercowitz and Sampson, 1991; Collard, 1999; Cassou and Lansing, 1998, 2006; Blackburn and Varvarigos, 2008), amongst others .[5]

The second specification (equation 4), directly derived from the assumption that leisure activity is home production.[6] In this case $h\mathcal{V}(\cdot)$ represents the utility of leisure activity captured as quality-adjusted leisure (see Stokey and Rebelo, 1995, who notes that leisure time is valued by human capital in the same way than working-time (production and education)).[7] Compared with the specification of $\mathcal{V}(\cdot)$ in equation (3), the specification of equation (4) captures the direct positive effect of human capital on utility. As emphasized by Benhabib et al. (1991), these two forms for $\mathcal{V}(\cdot)$ may lead to different results especially when human capital is a control variable. Because both forms have been used in the literature, we will investigate both cases.

For the ease of the exposition, we will use a "*general*" form for the function $\mathcal{V}(\cdot)$ that encompasses the two previous form:

$$\mathcal{V}(u(t) + e(t)) \equiv B(\mathbb{I} - (e(t) + u(t))^{1+\gamma}) \tag{5}$$

with $\mathbb{I}$ an indicator function capturing the two alternative specifications of the function $\mathcal{V}(\cdot)$ and thus defined as

$$\mathbb{I} = \begin{cases} 0, & \text{when disutility of forgone leisure is taken into account} \\ 1, & \text{when utility of leisure is taken into account} \end{cases}$$

Therefore the "*non-environmental*" instantaneous utility is:

$$U_{NE}(t) = \log[c(t) + h(t)B(\mathbb{I} - (e(t) + u(t))^{1+\gamma})] \tag{6}$$

The representative household also bears disutility from the stock of pollution in the economy (as conventional, see Xepapadeas, 2005):

$$U_E(t) = -\eta \log S(t), \tag{7}$$

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[4] Blackburn and Varvarigos (2008) note that "*it provides the necessary technical condition for ensuring the existence of a meaningful equilibrium with non-negative solutions for both l and e.* [...] *More familiarly, one may see the assumption as reflecting the principle of diminishing marginal utility of leisure (translated into increasing marginal disutility of effort).*" (p.440). They also note that "[...]*empirical estimates and calibrated values of this parameter vary over a wide range, from as low as 1.3 to as high as 6.0*" (p.449).

[5] None of the aforementioned articles deal with environmental concerns

[6] See Appendix A for a justification in the case of our model. This assumption means that leisure is not looked for itself and is entirely used in home production activities. In appendix B, we consider the case that the agent values a part of his leisure time for itself and uses the remaining for home production. Results are not modified.

[7] Such a form has been used by Stokey and Rebelo (1995) but with an instantaneous utility not time-separable.

where U_E is the instantaneous "*environmental*" utility, S is the stock of pollution and $\eta \geq 0$ measures green preference. As a result, her lifetime utility is given by

$$\mathcal{U} = \int_0^\infty \left[\log\left(c + hB(\mathbb{I} - (e+u)^{1+\gamma})\right) - \eta \log S\right] \exp\left(-\varrho t\right) dt, \tag{8}$$

where ϱ is the discount factor.

The representative household faces the following budget constraint:

$$\dot{a}(t) = r(t)a(t) + w(t)u(t)h(t) - c(t)$$

where a represents financial assets, r is the interest rate in the economy and w the wage rate. She maximizes her lifetime utility subject to this budget constraint and to the evolution of her human capital (equation 1). Her problem is :

$$\begin{aligned}
\max_{c(t),u(t),e(t),a(t),h(t)} \quad & \int_0^\infty \left[\log(c(t) + h(t)B(\mathbb{I} - (e(t)+u(t))^{1+\gamma})) - \eta \log S(t)\right] \exp(-\varrho t) dt \\
\text{subject to} \quad & \dot{h}(t) = A_h e(t) h(t) \\
& \dot{a}(t) = r(t)a(t) + w(t)u(t)h(t) - c(t) \\
\text{and} \quad & a(0) = ao > 0, \qquad h(0) = ho > 0
\end{aligned}$$

We have the folllowing current-value Hamiltonian for this program[8]

$$\mathcal{H} = \log(c + hB(\mathbb{I} - (e+u)^{1+\gamma})) - \eta \log S + q_1 \left[ra + wuh - c\right] + q_2 \left[A_h e h\right]$$

where q_1 is the shadow price of physical capital and q_2 is the shadow price of human capital. Denoting

$$\tilde{c} \equiv c + hB(\mathbb{I} - (e+u)^{1+\gamma}) > 0, \tag{9}$$

first-order conditions are

$$\frac{\partial \mathcal{H}}{\partial c} = 0 \qquad \Rightarrow \qquad \tilde{c}^{-1} = q_1 \tag{10}$$

$$\frac{\partial \mathcal{H}}{\partial e} = 0 \qquad \Rightarrow \qquad -B(1+\gamma)(u+e)^\gamma \tilde{c}^{-1} = q_2 A_h \tag{11}$$

$$\frac{\partial \mathcal{H}}{\partial u} = 0 \qquad \Rightarrow \qquad -B(1+\gamma)(u+e)^\gamma \tilde{c}^{-1} = q_1 w \tag{12}$$

$$\frac{\partial \mathcal{H}}{\partial a} = -\dot{q}_1 + \varrho q_1 \qquad \Rightarrow \qquad r q_1 = -\dot{q}_1 + \varrho q_1 \tag{13}$$

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[8] Temporal indexes are suppressed when there is no ambiguity.

$$\frac{\partial \mathcal{H}}{\partial h} = -\dot{q}_2 + \varrho q_2 \qquad \Rightarrow \qquad B(\mathbb{I} - (e+u)^{1+\gamma})\tilde{c}^{-1} + q_1 w u + q_2 A_h e = -\dot{q}_2 + \varrho q_2 \tag{14}$$

with the transversality conditions

$$\lim_{t\to\infty} q_1 a \exp(-\varrho t) = 0$$

$$\lim_{t\to\infty} q_2 h \exp(-\varrho t) = 0$$

Equations (11) and (12) yield

$$q_1 w = q_2 A_h \tag{15}$$

and equation (13) gives

$$\dot{q}_1 = (\varrho - r) q_1 \tag{16}$$

Using (11) and (15), equation (14) is written as

$$\frac{\dot{q}_2}{q_2} = \varrho - A_h \left[u + e - \left(\frac{e+u}{1+\gamma} - \frac{\mathbb{I}}{(1+\gamma)} (u+e)^{-\gamma} \right) \right] \tag{17}$$

Differentiating (15) with respect to time and using equations (16) and (17) we obtain:

$$r(t) = A_h(u(t)+e(t)) - A_h \left(\frac{e(t)+u(t)}{1+\gamma} - \frac{\mathbb{I}}{(1+\gamma)} (u(t)+e(t))^{-\gamma} \right) + \frac{\dot{w(t)}}{w(t)}, \tag{18}$$

This equation means that the returns to physical capital investment (the left-hand side) equal the returns to human capital investment (the right-hand side). Conversely to the Lucas (1988) model with inelastic labour supply and conversely to the Hettich (1998) model with time-nonseparable utility and elastic labour supply, the exogenous productivity parameter in the educational sector A_h and the evolution of the wage rate are not the only determinants of the returns to human capital investment anymore.

The influence of working-time on the returns to human capital accumulation appears through the first term into brackets in the right-hand side of the equation (18). The term $A_h(u+e)$ represents the pecuniary gains to increase the stock of human capital by one unit: gains in terms of additional qualified labor u and gains in terms of higher human capital accumulation through e. The term $-A_h \left(\frac{e+u}{1+\gamma} - \frac{\mathbb{I}}{(1+\gamma)} (u+e)^{-\gamma} \right)$ represents the cost in terms of utility to increase the stock of human capital. It is proportional to the amount of non-leisure time $u+e$, because the higher non-leisure time the greater the disutility of human capital. In order to compare with the case of inelastic labor supply, we let the parameter γ to tend towards infinity (that is the

the intertemporal elasticity of substitution in labor supply $1/\gamma$ tends towards 0) and we put $u + e = 1$. In that case, the left-hand side of equation (18) equals A_h like in Lucas (1988).

The equations (10) and (12) equate the total amount of time devoted to working activities to the current wage rate:

$$u(t) + e(t) = (\mu w(t))^{1/\gamma} \tag{19}$$

with $\mu \equiv [(1+\gamma)B]^{-1}$ and $B > (1+\gamma)^{-1} w(t)$ because $u + e \in]0, 1[$. Due to the time-separability of preferences, the marginal rate of substitution between consumption and labor supply does not depend on consumption.

Finally, the intertemporal law of motion of consumption is obtained by differentiating equation (10) with respect to time and by using equations (9) and (16):

$$\begin{aligned} \frac{\dot{c(t)}}{c(t)} &= r(t) - \varrho - B(\mathbb{I} - (e(t) + u(t))^{1+\gamma}) \frac{h(t)}{c(t)} \times \\ & \left(A_h e(t) + \varrho - r(t) - (\dot{e}(t) + \dot{u}(t)) \left(\frac{e(t) + u(t)}{1+\gamma} - \frac{\mathbb{I}}{(1+\gamma)} (u(t) + e(t))^{-\gamma} \right)^{-1} \right) \end{aligned} \tag{20}$$

The last term in the right-hand side of the equation captures the influence of the working-time disutility on the intertemporal decision to consume. Let suppose that $B = 0$: we obtain the well-known Keynes-Ramsey rule.

2.2 Firms and pollution

Final output y is produced under perfect competition using the following constant-returns to scale Cobb-Douglas technology:

$$y(t) = A_y k(t)^{\alpha_k} (u(t)h(t))^{\alpha_u} p(t)^{\alpha_p}, \qquad \alpha_k, \alpha_u, \alpha_p \in]0, 1[\text{ and } \alpha_k + \alpha_u + \alpha_p = 1$$

where $A_y > 0$ is a productivity scalar, k is the stock of physical capital, uh is the amount of human capital allocated to the production sector and p is emissions of pollution. Firms support a tax τ, implemented by the government, on each unit of pollutant emissions they create. They maximize profit $y(t) - r(t)k(t) - w(t)u(t)h(t) - \tau p(t)$ by equating factors return to their marginal productivity:

$$r(t) = \alpha_k y(t)/k(t) \tag{21}$$

$$w(t) = \alpha_u y(t)/(h(t)u(t)) \tag{22}$$

and by equating the marginal cost of the pollutant emissions to their marginal productivity:

$$\tau = \alpha_p y(t)/p(t) \tag{23}$$

Thus, we can express the final output as a function of the physical capital stock, the human capital allocated to production and the environmental tax rate:

$$y(t) = \mathcal{A}(\tau;\alpha_p,\beta)k(t)^{\alpha}(h(t)u(t))^{1-\alpha} \tag{24}$$

where $\mathcal{A}(\tau;\alpha_p,\beta) \equiv A_y^{\beta}\alpha_p^{\alpha_p\beta}\tau^{-\alpha_p\beta}$, $\alpha \equiv \alpha_k\beta$ and $\beta \equiv 1/(\alpha_k+\alpha_u)$.

The stock of pollution, S, evolves according to two opposite forces. On the one hand, it increases in the net flow of pollution $p(t)/d(t)$, where d is the abatement publicly provided by the government. On the other hand, it decreases due to a natural rate of decay $\zeta > 0$, such that $\dot{S}(t) = [p(t)/d(t)]^{\chi} - \zeta S(t)$, where $\chi > 0$ is the exogenous elasticity of pollution stock with respect to the net flow of pollution p/d. Because the fruit of the environmental tax $\tau p(t)$ is used to finance the public abatement activities $d(t)$, the law of motion of the stock of pollution reduces to:

$$\dot{S}(t) = \tau^{-\chi} - \zeta S(t). \tag{25}$$

From equations (21), (22) and (24), the interest rate and the wage rate may be expressed as a function of the environmental tax τ:

$$r(t) = \alpha_k\mathcal{A}(\tau;\alpha_p,\beta)\left(\frac{k(t)}{h(t)u(t)}\right)^{\alpha-1} \tag{26}$$

and

$$w(t) = \alpha_u\mathcal{A}(\tau;\alpha_p,\beta)\left(\frac{k(t)}{h(t)u(t)}\right)^{\alpha} \tag{27}$$

Differentiating this equation with respect to time (using equations (18), (19) and (26)) gives

$$\alpha\frac{\dot{u}}{u} = \alpha\left(\frac{\dot{k}}{k}-\frac{\dot{h}}{h}\right) - \alpha_k\mathcal{A}(\tau;\alpha_p,\beta)\left(\frac{k}{hu}\right)^{\alpha-1} + A_h\left[u+e-\left(\frac{e+u}{1+\gamma}-\frac{\mathbb{I}}{(1+\gamma)}(u+e)^{-\gamma}\right)\right] \tag{28}$$

2.3 Market equilibria

Factor markets clear instantaneously and financial market equilibrium implies that household's claims of capital equal the physical capital stock ($a = k$). Final output is used either for consumption, either for investment in physical capital or for abatement activities (using final output one for one), therefore

$$y(t) = c(t) + \dot{k}(t) + d(t)$$

Because we assumed that the government budget is balanced all the time – that is $\tau p = d$ –, from equation (23) the final output market equilibrium is rewritten as:

$$(1-\alpha_p)y(t) = c(t) + \dot{k}(t) \tag{29}$$

3 General equilibrium and the Balanced growth path

Let define $b \equiv h/k$ and $x \equiv c/k$, therefore the economy is summarized by:

$$\begin{aligned}\frac{\dot{x}}{x} &= (\alpha_k + \alpha_p - 1)\mathcal{A}(\tau;\alpha_p,\beta)\,(bu)^{1-\alpha} + x - \varrho \\ &- B(\mathbb{I} - (e+u)^{1+\gamma})\frac{h}{c}\times \\ &\quad\left\{A_h e + \varrho - \alpha_k\mathcal{A}(\tau;\alpha_p,\beta)\,(bu)^{1-\alpha} - (\dot{u}+\dot{e})\left(\frac{e+u}{1+\gamma} - \frac{\mathbb{I}}{(1+\gamma)}(u+e)^{-\gamma}\right)^{-1}\right\}\end{aligned} \tag{30}$$

$$\frac{\dot{b}}{b} = A_h e - (1-\alpha_p)\mathcal{A}(\tau;\alpha_p,\beta)\,(bu)^{1-\alpha} + x \tag{31}$$

$$\frac{\dot{u}}{u} = \frac{\dot{b}}{b} - (\alpha_k + \alpha_u)\mathcal{A}(\tau;\alpha_p,\beta)\,(bu)^{1-\alpha} + \frac{A_h}{\alpha}\left[u + e - \left(\frac{e+u}{1+\gamma} - \frac{\mathbb{I}}{(1+\gamma)}(u+e)^{-\gamma}\right)\right] \tag{32}$$

$$u + e = \left[\frac{\alpha_u\mathcal{A}(\tau;\alpha_p,\beta)}{B(1+\gamma)}\,(bu)^{-\alpha}\right]^{1/\gamma} \tag{33}$$

$$\alpha \equiv \frac{\alpha_k}{\alpha_k + \alpha_u} \tag{34}$$

We restrict our attention to the steady-state equilibrium defined as a balanced growth path where c, h, k and y grow at the same endogenous positive rate of growth $g^\star$ and where u, e, S, w and r are constant.

Using the fact that $\dot{x} = \dot{b} = 0$, from equations (30) and (31), we obtain (a star refers to steady-state value):

$$\left[1 + B(\mathbb{I} - (e^\star + u^\star)^{1+\gamma})\frac{b^\star}{x^\star}\right]\left[\alpha_k\mathcal{A}(\tau;\alpha_p,\beta)\,(b^\star u^\star)^{1-\alpha} - \varrho - A_h e^\star\right] = 0 \tag{35}$$

The first term into brackets in the left-hand side of the equation is U_{NE}/c evaluated along the BGP (see equation 2). Because the instantaneous non-environmental utility must be positive at all times, the previous equality imposes that

$$\alpha_k \mathcal{A}(\tau;\alpha_p,\beta)\,(b^\star u^\star)^{1-\alpha} - \varrho = A_h e^\star = g^\star \tag{36}$$

Using the fact that $\dot{u} = 0$ along the BGP, from equations (32) and (33), we obtain:[9]

$$\alpha_k \left(\frac{\alpha_u}{B(1+\gamma)}\right)^{(1-\alpha)/\alpha} \mathcal{A}(\tau;\alpha_p,\beta)^{1/\alpha}(u^\star+e^\star)^{-\gamma(1-2\alpha)/\alpha} = \frac{A_h}{1+\gamma}\left[\mathbb{I} + \gamma(u^\star+e^\star)^{1+\gamma}\right] \tag{37}$$

that defines implicitly the forgone leisure along the BGP $u^\star + e^\star$ as a function of τ, denoted $\mathcal{E}_{\mathbb{I}}(\tau)$. As we will demonstrate in the next section, the influence of τ on $u^\star + e^\star$ is related to the value of $\mathbb{I}$.

From (33) and (36), we can express the growth rate along the BGP as a function of the environmental tax: $g^\star = \alpha_k \left(\frac{\alpha_u}{B(1+\gamma)}\right)^{(1-\alpha)/\alpha} \mathcal{A}(\tau;\alpha_p,\beta)^{1/\alpha}(u^\star+e^\star)^{-\gamma(1-\alpha)/\alpha} - \varrho$. And from equation (37), we obtain

$$g^\star_{\mathbb{I}} = \frac{A_h}{1+\gamma}\mathcal{E}_{\mathbb{I}}(\tau)^{-\gamma}\left[\mathbb{I} + \gamma\mathcal{E}_{\mathbb{I}}(\tau)^{1+\gamma}\right] - \varrho \tag{38}$$

The rate of growth along the Balanced growth path is affected by the environmental tax according to the specification of the function $\mathcal{V}(\cdot)$ used in preferences.

4 Environmental policy and human capital accumulation

In this section we investigate the features of the BGP equilibrium, and the impact of the environmental tax on the BGP rate of growth according to the assumption on preferences (either $\mathbb{I} = 0$ or $\mathbb{I} = 1$).

Case 1: the "disutility of quality-adujsted forgone leisure" specification

In such a case, $\mathbb{I} = 0$ and the instantaneous non-environmental utility is written as:

$$U_{NE} = \log\left(c - B(u+e)^{1+\gamma}\right) \tag{39}$$

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[9] $\dot{u} = \dot{b} = 0$ implies that $\alpha_k \mathcal{A}(\tau;\alpha_p,\beta)\,(b^\star u^\star)^{1-\alpha} = A_h\left[u^\star + e^\star - \left(\frac{e^\star+u^\star}{1+\gamma} - \frac{\mathbb{I}}{(1+\gamma)}(u^\star+e^\star)^{-\gamma}\right)\right]$. And from (33), $b^\star u^\star = \left[\frac{\alpha_u \mathcal{A}(\tau;\alpha_p,\beta)(u^\star+e^\star)^{-\gamma}}{B(1+\gamma)}\right]^{1/\alpha}$. Putting this expression in the previous equation gives the result.

The solution of equation (37) may be explicitly written

$$\mathcal{E}_0(\tau) \equiv \left[\frac{1+\gamma}{\gamma A_h} \alpha_k \left(\frac{\alpha_u}{B(1+\gamma)} \right)^{(1-\alpha)/\alpha} \mathcal{A}(\tau; \alpha_p, \beta)^{1/\alpha} \right]^{\frac{\alpha}{\alpha+\gamma(1-\alpha)}} \tag{40}$$

and is decreasing in τ because $\mathcal{A}(\tau; \alpha_p, \beta)$ is a decreasing in τ. The growth rate along the BGP is expressed as (from equation 38):

$$g_0^\star = \frac{A_h}{1+\gamma} \gamma \mathcal{E}_0(\tau) - \varrho \tag{41}$$

From this expression, it comes the following proposition.

Proposition 1. *With time separable utility and human capital enters the preferences through the quality-adujsted disutility of forgone leisure (working time), a tighter environmental tax reduces human capital accumulation and growth along the balanced growth path, when the source of pollution is final output.*

Proof. Straightforward from equations (40) and (41). □

Proposition 1 contrasts with the results found in the literature. Indeed, with endogenous labour supply and time-nonseparable utility function including "*non-adjusted*" leisure, Hettich (1998) finds that the environmental policy promotes human capital accumulation when the source of pollution is physical capital. When the environmental tax increases, firms rise their abatement activities at the expense of final output and consumption is reduced. With time-nonseparable utility, the amount of leisure chosen by each agent depends positively on her level of consumption and negatively on her amount of labour income. As a result, the agent reduces her leisure and reallocates her time into productive activities. That boosts growth. Conversely, when the source of pollution is final output, Hettich (1998) finds no impact of the environmental tax on the growth rate because wage and consumption diminishes in the same amount and let unchanged leisure time.

In our framework, leisure (captured by working time) only depends on the wage rate because of the time-separability of preferences. Furthermore, a greater amount of human capital increases the disutility of working activities (output production and education) because we assume home production. As a result, the returns to education in the steady-state do not only depend on the exogenous productivity parameter in the education sector anymore (see equation 18), conversely to Lucas (1988) or Hettich (1998). The returns to human capital accumulation are positively influenced by the amount of working-time (see details page 8). Because a tighter environmental taxation reduces the wage rate, working-time diminishes as well (see equation 19). The returns to education fall and agents invest less in human capital accumulation. The environmental policy is detrimental for growth.

It is straightforward that our results rely on the time-separable form of the utility function and on the assumption that $\gamma > 0$. Furthermore, the size of the negative impact of the environmental taxation on growth depends on the value of the the intertemporal elasticity of substitution in labor supply $1/\gamma$, in a way that is not easy to find analytically That is the reason why we perform a numerical application to investigate the influence of parameter γ on our results.

We first calibrate the model. In an ad-hoc manner we assume that χ the elasticity of pollution with respect to the ratio p/d is fixed to 1 and the benchmark value of the environmental tax rate τ is arbitrary chosen to 5% (we will modify later this value to investigate the impact of the environmental tax). We choose other parameters to replicate the calibration made by Cassou and Lansing (2006).[10] That is $\gamma = 5$ to obtain a the intertemporal elasticity of substitution in labor supply $1/\gamma = 0.2$, the after-tax interest rate $r^\star$ is equal to 4%, the average share of physical capital in output equal to $\alpha = 0.4$, the fraction of time in market work is $l^\star = 0.17$, the fraction of time in school or training is $e^\star = 0.12$ in the benchmark steady-state (Cf. Cassou and Lansing, 2006, p.647). Therefore, from equations (21) and (24), we choose $\alpha_k = 1/3$, $\alpha_u = 1/2$ and $\alpha_p = 1/6$ to obtain $\alpha = 0.4$ and we impose $A_y = 0.09404$ to obtain $r^\star = 0.04$. Because $e^\star = 0.12$, from equations (19) and (18) with $\dot{w} = 0$ in the steady-state, we fix $A_h = 0.1655$. Therefore, we obtain the per capita rate of ouput growth $g^\star = 0.1655 \times 0.12 = 1.986\%$, close to the 1.80% reported by Cassou and Lansing (2006), and the time preference parameter is $\varrho = 0.0201$. From equations (28) and (36) the wage rate in the steady-state is $w^\star = 0.02715$ and from equation (19), we impose $B = 2.20606$. The natural decay of pollution stock is fixed to $\zeta = 0.1$ and the parameter that captures green preferences is $\eta = 0.1$. The benchmark parameter values are reported in Table 1 and the corresponding steady-state value of the key variables are reported in Table 2.

A_h	A_y	γ	α_k	α_u	α_p	η, ζ	χ	B	ϱ	τ
0.1655	0.09404	5	1/3	1/2	1/6	0.1	1	2.20606	0.0201	0.05

Table 1: Parameter values.

We compute the effect of the environmental taxation on growth with respect to the value

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[10] We are aware that Cassou and Lansing (2006) do not deal with environmental concerns. Nevertheless, they try to replicate a part of the reality, and for this reason we adopt some parameter values they choose.

$g^\star$	$w^\star$	$r^\star$	$l^\star$	$e^\star$	$S^\star$	$W^{\star(1)}$
1.986%	0.1459	0.04	0.17	0.12	200	37.52

(1) indiv. welfare in the steady-state competitive equilibrium

Table 2: Key variable values in the steady-state

of the the intertemporal elasticity of substitution in labor supply and we report the results in Tables 3 and 4.[11] Values reported in Table 3 confirm our theoretical result : whatever the intertemporal elasticity of substitution in labor supply, a higher environmental tax is harmful to growth. Moreover, for the chosen parameter values, our numerical application shows that the marginal effect of the tax on the growth rate ($\Delta g^\star/\Delta\tau$) is increasing in the intertemporal elasticity of substitution in labor supply: for lower values of the intertemporal elasticity of substitution in labor supply (higher values of γ), the marginal effect is lowered (see Table 4). Especially, for γ equal to 10^6 – that is for a very low value of the intertemporal elasticity of substitution in labor supply – Table 4 shows that the marginal effect of the tax on the growth rate is infinitesimal. This result may be understood by remembering that when γ tends to infinity, labor supply becomes inelastic and we are in the Gradus and Smulders (1993)' case where the environmental policy does not influence growth.

Therefore, we can state:

Proposition 2. *For the chosen parameter values, our numerical application shows that the marginal effect of the environmental tax on the steady-state growth rate increases in the intertemporal elasticity of substitution in labor supply: for lower values of the intertemporal elasticity of substitution in labor supply, the marginal effect is lowered. When the intertemporal elasticity of substitution in labor supply tends towards infinity, the negative impact of the environmental taxation on growth vanishes.*

Proof. See Tables 3 and 4. □

We also examine the impact of the environmental taxation on the individual welfare, with respect to the intertemporal elasticity of substitution in labor supply. We compare steady-state individual welfare and therefore we do not take into account the gains or losses during the transition. Following Bovenberg and Heijdra (1998), we decompose welfare into two components:

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[11] Note that the minimal value of γ is 3.5 because lower values give negative growth rate whatever the value of the environmental tax τ.

τ γ	0.01	0.02	**0.05**	0.1	0.2	0.3	0.5
3,5	0.93	0.77	0.58	0.44	0.30	0.23	0.14
4	1.44	1.28	1,07	0.92	0.78	0.70	0.60
5	2.38	2.21	1.99	1.83	1.67	1.59	1.48
7.5	4.29	4.11	3.89	3.72	3.56	3.47	3.36
10	5.69	5.52	5.31	5.15	5.00	4.91	4.80
20	8.78	8.66	8.51	8.39	8.27	8.21	8.12
50	11.65	11.58	11.50	11.44	11.38	11.34	11.30
10^6 (1)	14.537606	14.537602	14.537597	14.537593	14.537590	14.537588	14.537585

(1) This value corresponds to a very low elasticity of labor supply.

Table 3: $g^\star$ (in %) with respect to γ and τ

$\Delta\tau$ γ	0.01→0.02	0.02→0.05	0.05→0.1	0.1→0.2	0.2→0.3	0.3→0.5
3.5	-0.1589	-0.0657	-0.0279	-0.0132	-0.0074	-0,0045
4	-0.1669	-0.0695	-0.0298	-0.0142	-0.0080	-0.0049
5	-0.1757	-0.0738	-0.0320	-0.0153	-0.0087	-0.0053
7.5	-0.1758	-0.0750	-0.0329	-0.0160	-0.0092	-0.0057
10	-0.1651	-0.0709	-0.0314	-0.0154	-0.0088	-0.0055
20	-0.1200	-0.0522	-0.0234	-0.0116	-0.0067	-0.0042
50	-0.0621	-0.0272	-0.0123	-0.0061	-0.0036	-0.0022
10^6	-4×10^{-6}	-1.66×10^{-6}	-8×10^{-7}	-3×10^{-7}	-2×10^{-7}	-1.5×10^{-7}

Table 4: $\Delta g^\star/\Delta\tau$ with respect to γ and τ

[12]

$$W_N \equiv \int_0^\infty \log\left(c^\star(t) - Bh^\star(t)(l^\star+e^\star)^{1+\gamma}\right)\exp(-\varrho t)dt = \frac{1}{\varrho}\left(\frac{g^\star}{\varrho} + \log\left(1 - B(l^\star+e^\star)^{1+\gamma}\right)\right) \tag{42}$$

is called "*non-environmental welfare*" and

$$W_E \equiv \int_0^\infty -\eta\log S^\star \exp(-\varrho t)dt = \frac{-\eta}{\varrho}\log\left(\frac{\tau^{-\chi}}{\zeta}\right) \tag{43}$$

is called "*environmental welfare*". Tables 5 and 6 report results of the numerical application for a low green preferences ($\eta = 0.1$) and for higher green preferences ($\eta = 0.3$). In the benchmark case ($\gamma = 5$) and in the case where γ is high ($\gamma = 10^6$), we report the values of W_N and W_E to highlight how the evolutions of welfare components influence in opposite directions total welfare.

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[12] For convenience, we choose $c(0) = h(0) = 1$.

τ γ	0.01	0.02	**0.05**	0.1	0.2	0.3	0.5
4	20.60	18.00	14.85	12.68	10.69	9.60	8.31
5	43.82	41.00	37.52	35.08	32.80	31.53	30.01
.. W_N	58.72	54.40	48.95	45.01	41.24	39.10	36.47
.. W_E	-14.90	-13.40	-11.43	-9.93	-8.44	-7.56	-6.46
7.5	108.22	102.51	95.44	90.45	85.74	83.13	79.96
10	125.36	122.79	119.52	117.15	114.86	113.56	111.96
20	233.58	225.30	214.96	207.60	200.61	196.69	191.92
50	272.27	272.23	272.20	272.18	272.16	272.16	272.15
10^6	343.58	345.08	347.05	348.55	350.04	350.92	352.02
... W_N	358.478530	358.478479	358.478355	358.478603	358.478166	358.478110	358.478041
... W_E	-14.89	-13.40	-11.43	-9.93	-8.44	-7.56	-6.46

Table 5: Individual welfare with respect to γ and τ, for $\eta = 0.1$

From Tables 5 and 6, the non-environmental welfare decreases in the environmental taxation because the steady-state rate of growth $g^\star$ and working time $l^\star + e^\star$ reduce. At the contrary, the environmental welfare increases because pollution stock diminishes. The impact of a tighter environmental tax on total welfare depends on the relative importance of green preferences, measured by η, and depends on the value of the intertemporal elasticity of substitution in labor supply. Thus, as reported in Table 5, when green preferences are low ($\eta = 0.1$), except for high values of γ, the effect on non-environmental welfare offsets the effect on environmental welfare and total welfare diminishes. Conversely, for higher green preferences ($\eta = 0.3$), the second effect wins, even if the intertemporal elasticity of substitution in labor supply is low, and total welfare increases with a tighter environmental tax (see Table 6).

PROPOSITION 3. *A tighter environmental policy reduces non-environmental welfare and increases environmental welfare. When green preferences are low, the impact on total welfare is negative except when the intertemporal elasticity of substitution in labor supply is low enough. When green preferences are high, the tighter environmental tax always increases total welfare.*

PROOF. See Tables 5 and 6. □

Case 2: the "utility of quality-adjusted leisure" specification

In such a case, $\mathbb{I} = 1$ and the instantaneous non-environmental utility is written as:

$$U_{NE} = \log\left(c + B(1 - (u+e)^{1+\gamma})\right) \tag{44}$$

γ \ τ	0.01	0.02	**0.05**	0.1	0.2	0.3	0.5
5	14.03	14.19	14.67	15.22	15.93	16.41	17.09
.. W_N	58.72	54.40	48.95	45.01	41.24	39.10	36.47
.. W_E	-44.69	-40.21	-34.28	-29.80	-25.31	-22.69	-19.38
7.5	61.00	61.16	61.55	61.98	62.52	62.89	63.40
10	95.56	95.98	96.67	97.29	97.99	98.44	99.04
20	171.89	173.41	175.48	177.09	178.72	179.69	180.93
50	242.48	245.43	249.34	252.31	255.29	257.03	259.23
10^6	3313.79	318.27	324.20	328.69	333.17	335.79	339.10
... W_N	358.478573	358.478479	358.478355	358.478603	358.478166	358.478110	358.478041
... W_E	-14.89	-13.40	-11.43	-9.93	-8.44	-7.56	-6.46

Table 6: Individual welfare with respect to γ and τ, for $\eta = 0.3$

Equation (37) is re-written as:

$$\alpha_k \left(\frac{\alpha_u}{B(1+\gamma)} \right)^{(1-\alpha)/\alpha} \mathcal{A}(\tau; \alpha_p, \beta)^{1/\alpha} (u^\star + e^\star)^{-\gamma(1-2\alpha)/\alpha} = \frac{A_h}{1+\gamma} \left[1 + \gamma (u^\star + e^\star)^{1+\gamma} \right] \quad (45)$$

that gives the implicit expression of $e^\star + u^\star$ as a decreasing function of τ (for the sufficient condition $\alpha \leq 1/2$) denoted by $\mathcal{E}_1(\tau)$.

The growth rate along the BGP is expressed as (from equation 38):

$$g_1^\star = \frac{A_h}{1+\gamma} \left[\mathcal{E}_1(\tau)^{-\gamma} + \gamma \mathcal{E}_1(\tau) \right] - \varrho \quad (46)$$

From this expression, it comes the following proposition.

Proposition 4. *With time separable utility and human capital enters the preferences through the quality-adujsted utility of leisure, if $\alpha_k \leq \alpha_u$ (the part of physical capital in production is lower than or equal to the part of labor), a tighter environmental tax increases human capital accumulation and growth along the balanced growth path, when the source of pollution is final output.*

Proof. We have

$$\frac{\partial g^\star}{\partial \tau} = \frac{\partial g^\star}{\partial \mathcal{E}_1(\tau)} \frac{\partial \mathcal{E}_1(\tau)}{\partial \tau} = \frac{-\gamma A_h}{1+\gamma} \left[\mathcal{E}_1(\tau)^{-1+\gamma} - 1 \right] \frac{\partial \mathcal{E}_1(\tau)}{\partial \tau} \quad (47)$$

The term into brackets in the RHS of the equation is positive because $\mathcal{E}_1(\tau) \in]0, 1[$ by definition. As a result $\frac{\partial g^\star}{\partial \mathcal{E}_1(\tau)} < 0$ and because $\frac{\partial \mathcal{E}_1(\tau)}{\partial \tau} < 0$, we obtain $\frac{\partial g^\star}{\partial \tau} > 0$.

$\square$

Thus, the positive impact of human capital in utility offsets the negative influence of the quality-adjusted disutility of working time, and the integration of home production leads to a positive impact of the environmental tax on growth.

5 Conclusion

The aim of this paper was to contribute to the understanding of the link between the environment and growth when the channel of transmission is education.

We demonstrate that a tighter environmental tax is harmful to growth in a model with human capital accumulation à la Lucas (1988), when preferences are time-separable and leisure enters utility through the disutility of working time adjusted by human capital (to take into account home production) . Indeed, in such a framework, working-time increases with the current wage rate and it is not affected by consumption due to the time-separability of preferences. Furthermore, the returns to education are positively influenced by working-time because the negative impact of working-time in preferences is adjusted by human capital. As a result, by reducing the wage rate, a tighter environmental tax leads agents to diminish their working-time. The returns to education fall and agents decide to invest less in human capital accumulation. The environmental policy is detrimental for growth.

We also demonstrate that the intertemporal elasticity of substitution in labor supply plays a crucial role in that result. Especially, performing a numerical application, we show that, for intermediate values of the intertemporal elasticity of substitution in labor supply, the detrimental impact of the environmental tax on growth increases in the intertemporal elasticity of substitution in labor supply, for the chosen parameter values. We also show that a tighter environmental tax reduces the individual steady-state welfare, except when the intertemporal elasticity of substitution in labor supply is low or green preferences are high enough.

Finally, integrating the positive influence of human capital into preferences by modelling home production activities, we demonstrate that in a model with human capital accumulation à la Lucas (1988), even if the output is the source of pollution, the environmental policy enhances growth when leisure is introduced into utility under the condition that leisure is adjusted by human capital. That result challenges the finding by Hettich (1998) according to which, in the presence of leisure, the environmental tax does not affect human capital accumulation if the source of pollution is output.

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Appendix A

Let us consider now that the representative household have the following preferences:

$$U = \int_0^\infty \log \bar{C}(t) e^{-\varrho t} dt \tag{48}$$

where $\bar{C}(t)$ now represents a composite consumption good encompassing market consumption (c) and home consumption (c_h):

$$\bar{C}(t) = c(t) + c_h(t) \tag{49}$$

The market consumption good is produced according to the production function (24) and the market supply side is described in section 2.2.

Home production is assumed to only require human capital and the time that is not allocated in education e and in the output sector u, such that:

$$c_h = B\left(1 - (e+l)^{1+\gamma}\right) h, \tag{50}$$

where parameter $\gamma > 0$ captures the fatigue effect.[13]

Using equations (49) and (50) in (48), we obtain

$$U = \int_0^\infty \left[\log\left(c - Bh(l+e)^{1+\gamma} + Bh\right) - \eta \log S\right] e^{-\varrho t} dt \tag{51}$$

which is similar to the lifetime utility given by equation (8) (with $\mathbb{I} = 1$) except that in (51) the direct effect of human capital in utility function Bh is taken into account.

Appendix B. Leisure activity, home production and leisure time

While in the previous sections we assumed that leisure is not looked for itself and is entirely used in home production activities, we now consider that the agents value leisure time for itself.

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[13] $\gamma > 0$ means that if an agent uses 60% of his time at work (production and education), he will have less than the remaining 40% of his time to use as home production because of fatigue.

Denoting leisure time by $l \in]0,1[$, we can write the intertemporal utility function as follows:

$$\mathcal{U} = \int_0^\infty \left[\log\left(c(t) + h(t)(1 - l(t) - (u(t)+e(t))^{1+\gamma}\right) + \nu \log(h(t)l(t)) - \eta \log S(t)\right] \exp\left(-\varrho t\right) dt,$$

where the positive impact of leisure is specified in terms of "*quality time*", that is captured by leisure time l multiplied by the level of human capital. As noted by (Milesi-Ferretti and Roubini, 1998b, p. 240), qualified leisure is when leisure is produced by hour and human capital.[14] This way to introduce leisure time into the analysis is compatible with our assumptions about household production and has been used in the real business cycle literature (e.g., Kydland and Prescott, 1982; Prescott, 1986) and in the literature of household production (e.g., Benhabib et al., 1991). It also has been used in the literature studying the dynamics of endogenous growth model with human capital accumulation (e.g., Stokey and Rebelo, 1995; Ortigueira and Santos, 1997; Ortigueira, 2000).

Conversely the aforementioned literature, the qualified leisure also enters utility negatively because it reduces the time available to be used in home production. Furthermore, conversely to previous section, the stock of human capital also enters positively through the qualified leisure. As a consequence, we could expect a additional positive effect of the environmental taxation on human capital accumulation though this channel. In a similar way, we could expect that the desire of leisure time of its own sake could reduce the positive impact of the environmental taxation higlighted in proposition 4. We investigate this point in the following.

$$\begin{array}{rl} \max & \displaystyle\int_0^\infty \left[\log(c(t) + h(t)B(1 - l(t) - (e(t)+u(t))^{1+\gamma})) + \nu \log(h(t)l(t)) - \eta \log S(t)\right] \exp(-\varrho t) dt \\ \text{subject to} & \dot{h}(t) = A_h e(t) h(t) \\ & \dot{a}(t) = r(t)a(t) + w(t)u(t)h(t) - c(t) \\ \text{and} & a(0) = ao > 0, \qquad h(0) = ho > 0 \end{array}$$

We have the folllowing current-value Hamiltonian for this program[15]

$$\mathcal{H} = \log(c + hB(1 - l - (e+u)^{1+\gamma})) + \nu \log(hl) - \eta \log S + q_1 \left[ra + wuh - c\right] + q_2 \left[A_h e h\right]$$

where q_1 is the shadow price of physical capital and q_2 is the shadow price of human capital. Denoting

$$\tilde{c}_l \equiv c + hB(1 - l - (e+u)^{1+\gamma}) > 0,$$

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[14] See Milesi-Ferretti and Roubini (1995, 1998a) for the distinctions between the three ways to capture leisure: home production, raw time and quality time.

[15] Temporal indexes are suppressed when there is no ambiguity.

Denoting leisure time by $l \in]0,1[$, we can write the intertemporal utility function as follows:

$$\mathcal{U} = \int_0^\infty \left[\log\left(c(t) + h(t)(1 - l(t) - (u(t) + e(t))^{1+\gamma}\right) + \nu \log(h(t)l(t)) - \eta \log S(t)\right] \exp(-\varrho t) dt,$$

where the positive impact of leisure is specified in terms of "*quality time*", that is captured by leisure time l multiplied by the level of human capital. As noted by (Milesi-Ferretti and Roubini, 1998b, p. 240), qualified leisure is when leisure is produced by hour and human capital.[14] This way to introduce leisure time into the analysis is compatible with our assumptions about household production and has been used in the real business cycle literature (e.g., Kydland and Prescott, 1982; Prescott, 1986) and in the literature of household production (e.g., Benhabib et al., 1991). It also has been used in the literature studying the dynamics of endogenous growth model with human capital accumulation (e.g., Stokey and Rebelo, 1995; Ortigueira and Santos, 1997; Ortigueira, 2000).

Conversely the aforementioned literature, the qualified leisure also enters utility negatively because it reduces the time available to be used in home production. Furthermore, conversely to previous section, the stock of human capital also enters positively through the qualified leisure. As a consequence, we could expect a additional positive effect of the environmental taxation on human capital accumulation though this channel. In a similar way, we could expect that the desire of leisure time of its own sake could reduce the positive impact of the environmental taxation higlighted in proposition 4. We investigate this point in the following.

$$\begin{array}{rl} \max & \displaystyle\int_0^\infty \left[\log(c(t) + h(t)B(1 - l(t) - (e(t) + u(t))^{1+\gamma})) + \nu \log(h(t)l(t)) - \eta \log S(t)\right] \exp(-\varrho t) dt \\ \text{subject to} & \dot{h}(t) = A_h e(t) h(t) \\ & \dot{a}(t) = r(t)a(t) + w(t)u(t)h(t) - c(t) \\ \text{and} & a(0) = ao > 0, \qquad h(0) = ho > 0 \end{array}$$

We have the folllowing current-value Hamiltonian for this program[15]

$$\mathcal{H} = \log(c + hB(1 - l - (e+u)^{1+\gamma})) + \nu \log(hl) - \eta \log S + q_1 [ra + wuh - c] + q_2 [A_h eh]$$

where q_1 is the shadow price of physical capital and q_2 is the shadow price of human capital. Denoting

$$\tilde{c}_l \equiv c + hB(1 - l - (e+u)^{1+\gamma}) > 0,$$

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[14] See Milesi-Ferretti and Roubini (1995, 1998a) for the distinctions between the three ways to capture leisure: home production, raw time and quality time.

[15] Temporal indexes are suppressed when there is no ambiguity.

first-order conditions are

$$\frac{\partial \mathcal{H}}{\partial c} = 0 \qquad \Rightarrow \qquad \tilde{c}_l^{-1} = q_1$$

$$\frac{\partial \mathcal{H}}{\partial e} = 0 \qquad \Rightarrow \qquad -B(1+\gamma)(u+e)^{\gamma}\tilde{c}_l^{-1} = q_2 A_h$$

$$\frac{\partial \mathcal{H}}{\partial u} = 0 \qquad \Rightarrow \qquad -B(1+\gamma)(u+e)^{\gamma}\tilde{c}_l^{-1} = q_1 w$$

$$\frac{\partial \mathcal{H}}{\partial l} = 0 \qquad \Rightarrow \qquad Bh\tilde{c}_l^{-1} = \nu l^{-1}$$

$$\frac{\partial \mathcal{H}}{\partial a} = -\dot{q}_1 + \varrho q_1 \qquad \Rightarrow \qquad r q_1 = -\dot{q}_1 + \varrho q_1$$

$$\frac{\partial \mathcal{H}}{\partial h} = -\dot{q}_2 + \varrho q_2 \qquad \Rightarrow \qquad B(1-l-(e+u)^{1+\gamma})\tilde{c}_l^{-1} + \nu h^{-1} + q_1 w u + q_2 A_h e = -\dot{q}_2 + \varrho q_2$$

Combining first-order conditions, we obtain

$$\frac{\dot{q}_2}{q_2} = \varrho - A_h \left[u + e - \frac{1}{1+\gamma}\left(u+e-(u+e)^{-\gamma}\right)\right]$$

which is similar to (17) for $\mathbb{I} = 1$. That is similar for all results except for the intertemporal evolution of consumption. Finally, the economy may be summarized as

$$\frac{\dot{x}}{x} = (\alpha_k + \alpha_p - 1)\mathcal{A}(\tau; \alpha_p, \beta)\,(bu)^{1-\alpha} + x - \varrho$$
$$- B(1-l-(e+u)^{1+\gamma})\frac{h}{c}\times$$
$$\left\{ A_h e + \varrho - \alpha_k \mathcal{A}(\tau; \alpha_p, \beta)\,(bu)^{1-\alpha} - \frac{\dot{l} + (1+\gamma)(u+e)^{\gamma}(\dot{u}+\dot{e})}{1-l-(u+e)^{1+\gamma}} \right\}$$

$$\frac{\dot{b}}{b} = A_h e - (1-\alpha_p)\mathcal{A}(\tau; \alpha_p, \beta)\,(bu)^{1-\alpha} + x$$

$$\frac{\dot{u}}{u} = \frac{\dot{b}}{b} - (\alpha_k + \alpha_u)\mathcal{A}(\tau; \alpha_p, \beta)\,(bu)^{1-\alpha} + \frac{A_h}{\alpha}\left[u + e - \left(\frac{e+u}{1+\gamma} - \frac{1}{(1+\gamma)}(u+e)^{-\gamma}\right)\right]$$

$$u + e = \left[\frac{\alpha_u \mathcal{A}(\tau; \alpha_p, \beta)}{B(1+\gamma)}\,(bu)^{-\alpha}\right]^{1/\gamma}$$

$$l = \frac{\nu}{1+\nu}\left[\frac{x}{Bb} + 1 - (u+e)^{1+\gamma}\right]$$

$$\alpha \equiv \frac{\alpha_k}{\alpha_k + \alpha_u}$$

Along the Balanced growth path, $l^{\star}$ is constant and $u^{\star} + e^{\star}$ remains the solution of equation (45) and is denoted $\mathcal{E}_1(\tau)$ which is a decreasing function of τ. The growth rate along the BGP is given by:

$$g_1^{\star} = \frac{A_h}{1+\gamma}\left[\mathcal{E}_1(\tau)^{-\gamma} + \gamma \mathcal{E}_1(\tau)\right] - \varrho$$

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