Pollution, Private Investment in Healthcare, and Environmental Policy*

Xavier Pautrel

LEMNA, University of Nantes, Chemin de la Censive du Tertre, Nantes, France.
xavier.pautrel@univ-nantes.fr

Abstract

This article demonstrates that, in a two-period overlapping generations model, the relationship between environmental taxation and economic activity (output level and growth) is inverted-U shaped when the detrimental impact of pollution on health and the individual decision of each working-age agent to improve her health are taken into account.

We also demonstrate that the link between environmental tax and lifetime welfare is inverted-U shaped as well, and that a tighter environmental policy may enhance economic activity while it reducing steady-state lifetime welfare. Finally, we investigate the social optimum and the determinants of the optimal environmental tax.

Keywords: Environment; health; overlapping generations

JEL classification: I1; Q58

I. Introduction

Is environmental policy harmful to economic activity, both in terms of output level and growth? Does a reduction in pollution imply such a heavy cost for the economy that the gains from a better environmental quality are not able to offset it? On a theoretical level, the answers are not clear-cut.

The aim of this article is to contribute to the debate on one of the more striking features of pollution: its detrimental impact on health. In contrast to previous work in the field, which take into account the impact of pollution on life expectancy

*I thank two anonymous referees for their helpful comments. All remaining errors are mine.

(i.e. mortality),[1] we focus on the influence of pollution on illness and disability (morbidity) due to the development of chronic diseases such as cancer, diabetes, hypertension, heart disease, pulmonary conditions and mental disorders.[2] A growing amount of empirical evidence has found a link between pollution and chronic disease and shows that even if pollution is not the main cause of these diseases, it is a contributory factor in their emergence and/or their deterioration.[3] In contrast to mortality, which affects mainly the old, illness and disability due to chronic disease primarily impact the working-age population, leading to significant losses in productivity and rising health expenditure for the 30-50 age group. According to the World Health Organization (WHO, 2004), in high-income countries, 56% of those suffering from some form of disease are people aged 15-59. As a result the development of chronic diseases has a major economic impact in terms of labor productivity, labor supply, education and savings, as shown by Suhrcke et al. (2006a).[4] It also places a burden on healthcare and welfare systems: Devol and Bedroussian (2007), from the Milken Institute, estimate that, for the United States, the seven most common chronic diseases represent a $277 billion annual expenditure on treatment and a loss in productivity equal to $1.1 trillion per year. Furthermore, chronic disease has

[1]See, among others, Jouvet et al. (2010), Mariani et al. (2009), Varvarigos (2008) or Pautrel (2008, 2009b).

[2]According to the WHO (2004, 2005), chronic diseases are responsible for 60% of all deaths worldwide and they are a major source of disability, especially in developing countries. Nevertheless, they affect developed countries as well (Suhrcke et al., 2006b; Zhang et al., 2008). Devol and Bedroussian (2007) find that more than half of all Americans (55.8%) were suffering from one or more chronic diseases in 2003.

[3]According to Briggs (2003) in the special issue of the British Medical Bulletin (issue 1, volume 68) about 8-9% of the total disease burden may be attributed to pollution in developed countries. Amongst others, Brook et al. (2004); Rajagopalan et al. (2005); Lang et al. (2008); Lee et al. (2007) show that different kinds of pollution are associated with cardiovascular diseases, diabetes and obesity (see the working paper version of this article (Pautrel, 2009a) for details).

[4]For the US in 2003, Davis et al. (2005) estimated that 55 million workers out of 148 million, aged 19 to 64 reported an inability to concentrate at work due to their own illness or that of a family member; 69 million workers reported missing days due to illness.

major implications in terms of occupational choices, which can not be supported (or funded) by the public healthcare system or insurance contracts.[5]

Rising health-expenditure for working-age people and the time they have to devote to managing chronic disease creates competition for resources that could be used in alternative ways, such as growth promoting activities or final production activities.[6] The main contribution of this article is to demonstrate that such resource competition is a channel of transmission between environmental policy, economic activity and welfare, when the detrimental impact of pollution on the health of the working-age population is taken into account.

To demonstrate this and to analyze its implications, we use a two-period overlapping generations model, in line with previous articles addressing intergenerational environmental issues,[7] introducing an explicit link between the environment and health. Following empirical evidence, we assume that health is negatively influenced by pollution but is improved by the investment in health-enhancing activities made by each agent during her working life.[8] Pollution is a by-product of final out-

[5]As emphasized by Mullahy and Robert (2008), increasing levels of physical activity is now viewed as a means to improve health outcomes. The US Department of Health and Human services advises that, in order to be in good health, a person should do 150 minutes of physical activity at moderate level or 75 minutes at vigourous level each week. In their study based on the Bureau of Labor Statistics' American Time Use Survey, Russell et al. (2007) noted that 11.3% of American adults (in 2003-2004) reported spending time (mean, 108 minutes) on activities related to health during the day before their interview and 5.6% (86 minutes) reported taking medicine, giving themselves a shot, exercising or therapy for medical reasons.

[6]Competition for resources in the relation between health and growth has been studied in several articles (see Dormont et al., 2007, for details and references). Nevertheless, most of these contributions view better health as an increase in life expectancy. Empirically, Dormont et al. (2006) find changes in morbidity that induce savings which more than offset the increase in spending due to population ageing.

[7]For example, John and Pecchenino (1994) analyze the potential conflict between economic growth and the maintenance of environmental quality when consumption degrades environmental quality while investment in environmental maintenance promotes it. See also John et al. (1995) who investigate the effects of environmental taxation distinguishing the horizon of the agents and the economy. For models with non-renewable resources, see Agnani et al. (2005), Kemp and Long (1979), Mourmouras (1991, 1993).

[8]Because we consider that the agents are suffering from chronic diseases that require medical

put production and in a competitive economy the government taxes final output to limit pollution emissions.

Our first contribution is to demonstrate that if the detrimental effect of pollution on health-status and an endogenous investment in health by the working-age population are taken into account, the link between environmental taxation and economic activity (final output level and growth) is inverted-U shaped. A tighter environmental policy has two opposite effects. First, because the environmental tax is imposed on final output, it reduces the rewards to production factor: the "*drag-down effect*". Secondly, it reduces pollution and therefore improves health-status of the working-age population. Agents reduce their investment in health-enhancing activities and the freed resources are used to increase consumption and production. This second effect, called the "*resource competition effect*", is positive. For low values of the environmental tax, the second effect offsets the first one, and the environmental policy promotes output and its growth rate. Furthermore, when the productivity effect of a better health status is taken into account, the environmental tax is more likely to increase final output.

Our second contribution is to find that an inverted-U shaped relationship between economic activity and an environmental tax also holds for steady-state lifetime welfare. Nevertheless, we demonstrate that under certain conditions about the share of consumption in utility and the share of physical capital in production, a tighter environmental policy may enhance economic activity while reducing steady-state lifetime welfare. This stems from the fact that, when the share of consumption in

care when they are young we do not assume that poor health agents expend more on medical care when they are elderly as Gutiérrez (2008) does. And, in contrast with Williams (2002, 2003), we do not assume that agents who are ill do not work.

utility is higher than the relative part of physical capital in production, the negative impact of the drag-down effect is greater for lifetime welfare than for final output and the positive impact of the competition for resources effect is lower for lifetime welfare than for final output. As a result, the negative impact of the environmental taxation exceeds the positive impact at a lower value for lifetime welfare than for final output.

Our third contribution is to show that the greater the room for improvement in health status, the more likely it is that the environmental policy will promote economic activity and growth. This effect occurs when the rate of natural health decay is low, the efficiency of healthcare spending is low, the weight of health in preferences is high, the share of labor in final output is high, the rate of natural purification of pollutants is low, the polluting capacity of production technology is high, the detrimental impact of pollution on health is high and the elasticity of pollution stock with respect to the net flow of pollution is high. Most of these criteria are satisfied in the most developed countries, and the detrimental impact of pollution on health being well-documented, our results show that an active environmental policy in these countries is highly likely to promote growth and output levels. In other words, the positive gains in terms of health and growth should be higher than the losses from factor rewards.

Finally, we investigate the social optimum and the optimal environmental tax. We demonstrate that the higher the weight of health in preferences, the elasticity of pollution stock with respect to the net flow of pollution, the detrimental impact of pollution on health and/or the part of labor in production, the higher the optimal environmental tax.

The article is organized as follows. Section 2 presents the model. Section 3 studies the competitive equilibrium and the impact of environmental taxation on the steady-state. Section 4 investigates the social optimum and the optimal environmental tax. Section 5 examines two extensions: AK endogenous growth and the impact of health on labor productivity. Section 6 concludes the article.

II. The model

Let's consider an overlapping generations model à la Diamond (1965) with endogenous preferences in health à la van Zon and Muysken (2001). A new generation is born at each date $t = 1, 2, ...$, and lives for two periods. The number of individuals born at time t is L. Population is constant. Individuals are non-altruistic: the old do not care for the young and the young do not care for the old. The preferences of an agent born in period t are represented by the following utility (from van Zon and Muysken (2001)):[9]

$$\log\left(c_{1t}^{\phi}h_t^{1-\phi}\right) + \theta\log\left(c_{2t+1}^{\phi}h_{t+1}^{1-\phi}\right), \tag{1}$$

where c_{1t} and c_{2t+1} are, respectively, consumption in youth and old age, h_t and h_{t+1} are respectively individual health-status in youth and in old age. Parameter $\theta = (1+\iota)^{-1}$ where $\iota > 0$ is the subjective discount rate of the agent. Parameter $\phi > 0$ (respectively $1-\phi$) captures the relative importance of consumption (respectively health), in utility.[10] Each young agent is endowed with one unit of time, supplying

[9]For simplicity, we use logarithmic preferences. A CRRA utility function could be used, like Agénor (2008), but it would make the model more complex with no improvement in the qualitative results. Proof upon request.

[10]Green preferences are not included, because it is assumed in the following that health status is affected by pollution.

$\nu_t \in]0,1[$ of this unit of time in final production and using the remaining time $1-\nu_t$, as an investment in healthcare activities to improve her health status.[11] She earns a wage income $\nu_t w_t$, where w_t is the wage rate.

The individual health status of an agent born at period t evolves between period t and period $t+1$ depending on two opposing forces (Aisa and Pueyo (2004)). On the one hand, biological processes involve a natural decay in health simply as time passes. Following Grossman (1972) and Cropper (1981) we further assume that health depreciates over time as a function of the stock of pollution (denoted S_t). On the other hand, the time invested in health-enhancing activities $(1-\nu_t)$ mitigates against this deterioration. Therefore, for an agent born at t, individual health-status evolves from period t to period $t+1$ as $h_{t+1} - h_t = \eta(1-\nu_t) - \xi S_t^{\gamma} h_t$ with $\eta > 0$ being the productivity scalar for health-enhancing activities.[12] Parameter $\gamma \geq 0$ measures the influence of pollution stock on the natural decay $\xi \in]0,1[$.[13]

A consumer, born at t, works during the first part of her life, consumes an amount c_{1t} and saves the remainder of her revenue. The budget constraint of a young agent

[11]We could assume that there is a sector that produces healthcare services using labor and therefore a part ν of labor is allocated to manufacturing production and a part $1-\nu$ is allocated to healthcare production. We would find the same qualitative results (proof upon request). Consequently, what we call *investment in health-enhancing activities* could be viewed as healthcare expenditure. Our modelling has the advantage of leading to a simpler exposition of the model and the results. Finally, results are not modified when leisure time is introduced. Proof upon request.

[12]Note that here, we model a linear relationship between the health-enhancing activities and the evolution of health-status which could be not empirically relevant. As demonstrated by Skinner et al. (2001): "*nearly 20 percent of total Medicare expenditure appears to provide no benefit in terms of survival, nor is it likely that this extra spending improves the quality of life*". Our assumption is made for simplicity. Note also that other authors (e.g. Bednarek et al., 2008) have considered a more general dynamic for health status but did not introduce the role of pollution in the health dynamics.

[13]We impose $\gamma \geq 0$ to investigate the absence of a detrimental impact of pollution on health, that is $\gamma = 0$. Nevertheless, it is expected that $\gamma > 1$, that is the higher the stock of pollution, the higher the detrimental effect of pollution, even if there is no empirical evidence on such a linear relationship.

is

$$c_{1t} + s_t = \nu_t w_t \tag{2}$$

where s_t denotes saving in youth. The budget constraint of an old person is

$$c_{2t+1} = (1 + r_{t+1})s_t \tag{3}$$

where r_{t+1} is the interest rate paid on savings held from period t to $t + 1$.

Firms operate through perfect competition using physical capital and labor to produce a final good with a constant returns-to-scale Cobb-Douglas technology, $Y_t = \tilde{A}_t K_t^{\alpha} N_t^{1-\alpha}$, where Y_t is the aggregate output, K_t is the aggregate productive capital, N_t is labor and $\alpha \in]0, 1[$. $\tilde{A}_t$ is a productive scalar, assumed as constant for the moment: $\tilde{A}_t \equiv A$. Capital depreciates fully in the production process.[14]

The stock of pollution S from period t to period $t + 1$ increases because of the net flow pollution in the current period t, denoted P_t and decreases according to the rate of natural purification of pollutants μ. The net flow of pollution at time t depends on pollution emissions at time t, denoted E_t, and on the abatement activities funded by the government, denoted D_t, such that $P_t = \mathcal{P}(E_t, D_t)$ where $\mathcal{P}_E(E_t, D_t) > 0$ and $\mathcal{P}_D(E_t, D_t) < 0$. We follow Gradus and Smulders (1993, 1996), Oueslati (2002), Varvarigos (2008), amongst others, by assuming that the function $\mathcal{P}(\cdot)$ is homogeneous of degree zero and may be written as $P_t = (E_t/D_t)^{\chi}$ where $\chi > 0$ is the exogenous elasticity of the pollution stock with respect to the ratio emissions to abatement services E/D. This specification is chosen for convenience: it is compatible with the case of endogenous growth that we will investigate at the

[14] The production process is over the course of a generation. If the annual depreciation rate is 10% (which is empirically relevant), 96% of the capital stock is depreciated over the course of a 30 year generation. Therefore, we assume that capital is fully used up in the production process. See De La Croix and Michel (2002) for further details.

end of this article,[15] and it makes the model as simple and as analytically tractable as possible, without loss of generality (see footnote 16 below). We assume that polluting emissions arise from final production such that $E_t = zY_t$ where parameter $z \in]0, 1[$ measures the polluting capacity of the technology. Abatement D_t is provided by the government as a public good and financed by the environmental tax τ on the source of pollution Y_t such that the public budget is balanced at each date: $D_t = \tau Y_t$. The law of motion of the stock of pollution is therefore $S_{t+1} = (z/\tau)^{\chi} + (1-\mu)S_t$ where $\mu \in]0, 1[$ is the the rate of natural purification of pollutants.[16]

III. Competitive equilibrium

A representative agent born in period t maximizes her utility function taking wages (w_t), the interest rate (r_{t+1}), the stock of pollution (S_t) and the current health-status (h_t) as given. She chooses consumption at both ages (c_{1t}, c_{2t+1}) and the proportion of time ν_t used in production:

$$\max_{\{c_{1t}, c_{2t+1}, \nu_t\}} \log\left(c_{1t}^{\phi} h_t^{1-\phi}\right) + \theta \log\left(c_{2t+1}^{\phi} h_{t+1}^{1-\phi}\right),$$

$$s.t. \begin{cases} c_{1t} + s_t = \nu_t w_t, \\ c_{2t+1} = (1 + r_{t+1})s_t, \\ h_{t+1} = \eta(1-\nu_t) + \left(1 - \xi S_t^{\gamma}\right) h_t. \end{cases}$$

[15] Such a specification of the net flow of pollution is used in most of the continuous-time endogenous growth models that deal with the environment (see the survey by Xepapadeas et al., 2005, for references) because it gives a constant stock of pollution in the long-run while the emissions and the abatement services grow constantly.

[16] The specification of the net flow of pollution we have chosen leads the dynamics of the stock of pollution to be independent of the economic activity at all times. Using a specification à la Varvarigos (2008) that makes the dynamics of the stock of pollution dependent on final output does not modify the qualitative results but makes the model more complex (proof upon request). We did not use the linear specification of the net flow of pollution à la John and Pecchenino (1994) (where $\mathcal{P} = E_t - D_t > 0$) because here abatement is public and $E_t - D_t = (z-\tau)Y_t > 0$ requires to assume $\tau < z$, which is uneasy to justify economically. Furthermore, it does not enable investigation of the case with endogenous growth because $E_t - D_t$ are not constant along the balanced growth path and therefore the stock of pollution explodes in the long-run.

The first-order condition and the consumer constraints give saving $s_t = \theta\nu_t w_t/(1+\theta)$ and the allocation of time to production $\nu_t = \phi(1+\theta)h_{t+1}/\left[\eta(1-\phi)\theta\right]$. Because $\nu_t \in]0,1[$, the health status of the old h_{t+1} is bounded to $\eta(1-\phi)\theta/[\phi(1+\theta)]$.[17]

Firms maximize their profit $\pi_t = (1-\tau)Y_t - (1+r_t)K_t - w_t N_t$. The demand for capital is given by

$$(1-\tau)\alpha Y_t/K_t = 1 + r_t \tag{4}$$

and the demand for labor is given by $(1-\tau)(1-\alpha)Y_t/N_t = w_t$. The good market clearing yields $K_{t+1} = s_t L$ and the labor market clearing equates labor demand N_t to labor supply $\nu_t L$: $N_t = \nu_t L$. Therefore, the competitive equilibrium may be defined by the following equations:

$$K_{t+1} = (1-\alpha)\left(\frac{\theta}{1+\theta}\right)(1-\tau)AK_t^{\alpha}(\nu_t L)^{1-\alpha}, \tag{5}$$

$$\nu_t = \frac{\phi(1+\theta)}{\eta(1-\phi)\theta}h_{t+1}, \tag{6}$$

$$h_{t+1} = \eta(1-\nu_t) + (1-\xi S_t^{\gamma})h_t, \tag{7}$$

and $S_{t+1} = (z/\tau)^{\chi} + (1-\mu)\, S_t$. From equations (6) and (7), we obtain the expression of the time not invested in health-enhancing activities but rather allocated to final production with respect to h_t, health status: $\nu_t = \phi(1+\theta)\left(1 + (1-\xi S_t^{\gamma})h_t/\eta\right)/(\phi + \theta)$. The higher the current health status h_t and the lower the current stock of pollution S_t, the lower the current time invested in health-enhancing activities $1-\nu_t$.

The steady-state is defined here as an equilibrium where physical capital, individual health-status, pollution stock, final output, the wage rate and the allocation of labor to production remain constant at any time at (respectively) $K^{\star}$, $h^{\star}$, $S^{\star}$, $Y^{\star}$,

[17] See van Zon and Muysken (1997, p.5) for a justification of the health status boundary.

$w^\star$ and $\nu^\star$, with $S^\star = \mathcal{S}(\tau) \equiv (z/\tau)^\chi/\mu$ and

$$h^\star = \mathcal{H}(\tau) \equiv \eta \left[\frac{\phi(1+\theta)}{(1-\phi)\theta} + \xi \left(\frac{(z/\tau)^\chi}{\mu} \right)^\gamma \right]^{-1}, \tag{8}$$

$$\nu^\star = \mathcal{V}(\tau) \equiv \phi \left[\phi + \frac{\xi(1-\phi)\theta}{(1+\theta)} \left(\frac{(z/\tau)^\chi}{\mu} \right)^\gamma \right]^{-1}. \tag{9}$$

Consequently, health status and the time allocated to production are positively affected by the environmental tax τ. From equations (5) and (9), the steady-state value of the physical capital stock is $K^\star = \mathcal{A}\ (1-\tau)^{1/(1-\alpha)}\mathcal{V}(\tau)$ with $\mathcal{A} \equiv ((1-\alpha)\theta A/(1+\theta))^{1/(1-\alpha)}\, L$. As $Y^\star = (1+\theta)K^\star/\left[\theta(1-\alpha)(1-\tau)\right]$,[18] we obtain the steady-state value of final output as a function of the environmental taxation τ: $Y^\star = \mathcal{A}_1\ (1-\tau)^{\alpha/(1-\alpha)} \left(\mathcal{B} + \xi\,(z^\chi/\mu)^\gamma\, \tau^{-\chi\gamma}\right)^{-1}$ with $\mathcal{A}_1 \equiv \mathcal{B}(1+\theta)\mathcal{A}/\left[\theta(1-\alpha)\right]$ and $\mathcal{B} \equiv \eta\phi(1+\theta)/[(1-\phi)\theta]$. Finally, the wage rate and savings at the steady-state are respectively given by:

$$w^\star = \left[\left(\frac{\theta}{1-\theta} \right)^\alpha (1-\alpha)A(1-\tau) \right]^{1/(1-\alpha)}, \tag{10}$$

$$s^\star = \phi \left[\left(\frac{\theta}{1-\theta} \right) (1-\alpha)A(1-\tau) \right]^{1/(1-\alpha)} \left[\phi + \frac{\xi(1-\phi)\theta}{(1+\theta)} \left(\frac{(z/\tau)^\chi}{\mu} \right)^\gamma \right]^{-1}.$$

Proposition 1. *When endogenous investment in individual health-status and the detrimental impact of pollution on health are taken into account, the relationship between the steady-state output and environmental taxation has an inverted-U shape. Below (respectively above) an environmental tax-level denoted $\hat{\tau}$ and defined as*

$$-\frac{\alpha}{1-\alpha}\mathcal{B}\hat{\tau}^{\chi\gamma} + \xi \left(\frac{z^\chi}{\mu} \right)^\gamma \left[\chi\gamma\left(\hat{\tau}^{-1} - 1\right) - \frac{\alpha}{1-\alpha} \right] = 0, \tag{11}$$

with $\hat{\tau} < (1-\alpha)\chi\gamma/[(1-\alpha)\chi\gamma + \alpha] < 1$, a tighter environmental taxation raises (respectively lowers) the steady-state level of output $Y^\star$.

[18]Note that $K_{t+1} = s_t L = \theta\nu_t(1-\tau)(1-\alpha)Y_t/((1+\theta)\nu_t) = \theta(1-\tau)(1-\alpha)Y_t/(1+\theta)$.

Proof. See Appendix A □

In equation (11), the first term in the LHS represents the negative impact of the environmental tax on the output rate of growth (i.e. the *drag-down effect*), and the last term represents the positive impact of the environmental tax on the output rate of growth (i.e. the *competition for resources effect*).[19] The environmental tax level $\hat{\tau}$ is the tax rate for which the *drag-down effect* and the *competition for resources effect* exactly offset each other.[20]

To understand the basic mechanism underlying Proposition 1, recall that

$$Y^{\star} = \mathcal{A}_1 \underbrace{(1-\tau)^{\frac{\alpha}{1-\alpha}}}_{Ia} \underbrace{\mathcal{V}(\tau)}_{Ib}. \tag{12}$$

Environmental tax influences the steady-state level of output through two channels: the direct impact of the environmental taxation on the rewards to labor (see overbrace *Ia* in equation 12) and the (indirect) impact on the allocation of labor in the manufacturing sector (see overbrace *Ib* in equation 12). The former (negative) is the well-known "*drag-down*" effect of the environmental tax that reduces factor rewards – captured by $(1-\tau)^{\alpha/(1-\alpha)}$. The latter (positive) is a new channel of transmission due to the "*competition for resources*" between health-enhancing activities and production activities, which affects the supply of labor to the final production sector $\nu^{\star} = \mathcal{V}(\tau)$. As pollution has a detrimental impact on the evolution of individual health-status, by reducing the net flow of pollution and therefore the stock of pollution, the environmental policy improves the individual health-status of the

[19]Note that we impose $\hat{\tau} < (1-\alpha)\chi\gamma/\left[(1-\alpha)\chi\gamma+\alpha\right] < 1$ to obtain a solution for $\hat{\tau}$ (See Appendix A).

[20]Note that the Bell relationship between tax rate and output implies a Laffer curve for the environmental taxation (proof upon request). We thank an anonymous referee for highlighting this point to us.

agents. Consequently, each agent decides to reduce her investment in health enhancing activities ($1-\nu^\star$ decreases) and to raise her labor supply to productive activities ($\nu^\star$ increases). In this way, the tighter environmental tax frees resources that were allocated to health enhancing activities and there are now reallocated to production, leading to a higher level of steady-state output and steady-state physical capital. Consequently the competition for resources between output production and health enhancing activities associated with the negative impact of pollution on health is the origin of a new channel through which the environmental policy may promote economic activity.

When $\gamma = 0$, changes in health-status are independent of pollution and therefore the investment of each agent in health-enhancing activities is not affected by the environmental tax: $\nu^\star$ is independent of τ. In such a case, the competition for resources is not affected by the environmental policy and only the "*drag-down*" effect remains: the environmental policy is detrimental for growth. Equally, the "*competition for resources effect*" no longer holds when there is no endogenous investment in health-enhancing activities.

Corollary 1. *Endogenous investment in health ($0 < \phi < 1$) and the detrimental impact of pollution on health ($\gamma > 0$) are two necessary conditions to obtain Proposition 1.*

Considering the influences of parameters on the environmental tax-level $\hat{\tau}$, enables us to understand why these two opposing effects of the environmental policy lead to an inverted-U shaped relationship between the environmental tax and the steady-state output level.

Proposition 2. *When the negative impact of the environment on health and the endogenous decision of each agent to invest her resources in health enhancing activities are taken into account, the environmental taxation will be more likely to improve the steady-state level of output if the rate of natural health decay (ξ) is low, the efficiency of healthcare spending (η) is low, the weight of health in preferences ($1-\phi$) is high, the share of labor in final output ($1-\alpha$) is high, the rate of natural purification of pollutants (μ) is low, and the polluting capacity of production technology (z) is high.*

Proof. Equation (11) gives the implicit expression of $\hat{\tau}$. Except for γ and χ, it is straightforward that $\partial\Gamma(\cdot)/\partial\xi > 0$, $\partial\Gamma(\cdot)/\partial\mathcal{B} < 0$, $\partial\Gamma(\cdot)/\partial\alpha < 0$, $\partial\Gamma(\cdot)/\partial\mu < 0$, $\partial\Gamma(\cdot)/\partial z > 0$, $\partial\Gamma(\cdot)/\partial\hat{\tau} < 0$. From the theorem of implicit function, we obtain $\partial\hat{\tau}/\partial\xi > 0$, $\partial\hat{\tau}/\partial\eta < 0$, $\partial\hat{\tau}/\partial\phi < 0$, $\partial\hat{\tau}/\partial\theta > 0$, $\partial\hat{\tau}/\partial\alpha < 0$, $\partial\hat{\tau}/\partial\mu < 0$ and $\partial\hat{\tau}/\partial z > 0$. □

When the detrimental effects of a polluted environment on health are large, the gains in terms of health of reducing pollutant emissions are very significant and the "*competition for resources effect*" that leads to an increase in labor supply has a greater influence than the "*drag-down effect*" that reduces factor rewards and, as a consequence, reduces saving and physical capital accumulation. Nevertheless, these positive gains diminish with the increase in the tax rate because the possible improvements in health-status due to the tax are reduced. At the same time, the losses from the reduction of factor rewards increase with the tax rate such that for the environmental tax-level $\hat{\tau}$, they offset the gains, and a further increase in τ leads to a decrease in the steady-state output level. Consequently, the greater the room for improving the environment and individual health-status through environmental policy, the more beneficial the environmental policy is likely to be for the economy.

As it is cumbersome to obtain analytically the influence of γ and χ on the tax-level $\hat{\tau}$,[21] we use a numerical application. We first calibrate the model assuming that the length of each period is 30 years, which is usual in the literature. The first period covers ages 20 to 50, and the second period covers ages 50 to 80. We use the U.S. economy as a benchmark. From De La Croix and Michel (2002), we choose α and θ following the standard choice in the RBC literature, that is $\alpha = 0.36$ and a quarterly psychological discount factor equal to 0.99. This implies that $\theta = 0.99^{(4\times30)} = 0.3$. We use the calibration by van Zon and Muysken (1997) for the values of ξ and ϕ. Parameter η, which measures the effectiveness of time invested into health-enhancing activities upon health status, is chosen by analogy with Skinner et al. (2001) who note that nearly 20% of total medical care expenditure provides no benefit to health. Thus we consider that only 80% of the time invested into health-enhancing activities benefits health-status: $\eta = 0.8$. Furthermore, because the value of parameter z seems to be important for determining the sign of the influence of χ and γ on $\hat{\tau}$ (see footnote 21) we will investigate a benchmark case $z = 0.3$ and the case where z is very low ($z = 0.01$). Finally, we set parameter A (the productive scalar in the manufacturing sector) equal to 50 to obtain positive welfare at the steady-state (denoted $W^{\star}$).[22] Benchmark value of parameters are summarized in Table 1:

z	α	θ	ϕ	ξ	A	η	L	χ	μ	γ
0.3	0.36	0.3	1/2	0.2	50	0.8	1	1	0.5	1.5

[21] We have $\partial\Gamma(\cdot)/\partial\chi = \alpha\left[\mathcal{B}\hat{\tau}^{\chi\gamma}\left(\chi^{-1} + \gamma\log z - \log\hat{\tau}\right) + \xi\left(z^{\chi}/\mu\right)^{\gamma}\right]/(1-\alpha) \gtreqless 0$ and $\partial\Gamma(\cdot)/\partial\gamma = \alpha\left[\mathcal{B}\hat{\tau}^{\chi\gamma}\left(\gamma^{-1} + \chi\log z - \log\mu - \chi\log\hat{\tau}\right) + \xi\gamma^{-1}\left(z^{\chi}/\mu\right)^{\gamma}\right]/(1-\alpha) \gtreqless 0$, because $(z, \mu, \hat{\tau}) \in]0, 1[$.

[22] Welfare at the steady-state is defined by the lifetime utility function (1) evaluated at the steady-state. It increases when parameter A increases (see Appendix B).

Table 1. Benchmark value of parameters

and the results of the numerical application are reported in Table 2 (where a variable with a hat and a star refers to a variable evaluated at the steady-state for an environmental tax equals to $\hat{\tau}$):

		$\hat{\tau}$	$\hat{Y}^\star$	$\hat{\nu}^\star$	$\hat{h}^\star$	$\hat{S}^\star$	$\hat{W}^\star$
	Benchmark	26.55%	111.884	0.865	0.160	2.260	1.165
$z = 0.3$	$\gamma = 0.5$	8.75%	130.462	0.892	0.165	6.859	1.427
	$\gamma = 1$	18.67%	119.359	0.871	0.161	3.213	1.278
	$\gamma = 2$	32.53%	106.645	0.864	0.160	1.844	1.079
	$\gamma = 2.5$	37.13%	102.831	0.867	0.160	1.616	1.012
	$\chi = 1.25$	28.96%	111.474	0.878	0.162	2.089	1.151
	$\chi = 1.5$	30.66%	111.448	0.889	0.164	1.936	1.144
	$\chi = 1.75$	31.87%	111.633	0.890	0.166	1.799	1.141
	$\chi = 2$	32, 74%	111.932	0.909	0.168	1.679	1.14
$z = 0.01$	$\gamma = 0.5$	3.086%	145.85	0.965	0.178	0.648	1.589
	$\gamma = 1$	3.92%	147.07	0.977	0.180	0.510	1.60
	$\gamma = 2$	3.96%	148.75	0.988	0.182	0.504	1.612
	$\gamma = 2.5$	3.84%	149.26	0.991	0.183	0.521	1.617
	$\chi = 1$	4.04%	148.05	0.984	0.182	0.495	1.605
	$\chi = 1.5$	3.33%	149.75	0.991	0.183	0.329	1.622
	$\chi = 2$	2.86%	150.626	0.994	0.184	0.244	1.631
	$\chi = 2.5$	2.54%	151.15	0.996	0.184	0.194	1.637

Table 2. Steady-state $\hat{\tau}$ for different values of γ and χ

Table 2 shows that for a very low value of z (0.01), an increase in γ, the influence of pollution stock on the natural decay of pollution, may reduce the threshold environmental tax level $\hat{\tau}$. An increase in χ, the elasticity of pollution stock with respect to the ratio of emissions to abatement services, reduces $\hat{\tau}$. We can find the reason for this influence by examining the derivatives in footnote 21: a very low value for z leads to a high negative value of $\log z$, which makes the derivatives negative. As it seems reasonable to assume that such a very low level of pollution emissions rate z is unrealistic, we consider that the influence of γ and χ on $\hat{\tau}$ is positive.

The influences of the parameters are summarized in the following table:

ξ	η	ϕ	θ	α	μ	z	χ	γ
$+$	$-$	$-$	$+$	$-$	$-$	$+$	$+^{(a)}$	$+^{(a)}$

(a) negative for z very low.

Table 3. Parameter Changes and Responses of $\hat{\tau}$

Finally, it is possible to investigate the impact of environmental taxation on the steady-state lifetime welfare, as well. This gives the following proposition.

Proposition 3. *There is an inverted-U shaped relationship between the steady-state lifetime welfare of an agent (denoted by $W^\star$) and the environmental tax. Below (respectively above) an environmental tax-level denoted $\hat{\tau}_W$ and defined as*

$$-\frac{\phi}{1-\alpha}\mathcal{B}\hat{\tau}_W^{\chi\gamma} + \xi\left(\frac{z^\chi}{\mu}\right)^\gamma\left[\gamma\chi(\hat{\tau}_W^{-1}-1) - \frac{\phi}{1-\alpha}\right] = 0, \tag{13}$$

with $\hat{\tau}_W < (1-\alpha)\chi\gamma/\left[(1-\alpha)\chi\gamma+\phi\right] < 1$, a tighter environmental taxation raises (respectively lowers) the steady-state lifetime welfare.

Proof. See Appendix B. □

Proposition 1 and Proposition 3 lead to

Corollary 2. *If $\phi > \alpha$ (respectively $\phi < \alpha$), then $\hat{\tau}_W < \hat{\tau}$ (resp. $\hat{\tau}_W > \hat{\tau}$). And if $\phi = \alpha$, then $\hat{\tau}_W = \hat{\tau}$. Therefore, if $\phi > \alpha$, when $\tau < \hat{\tau}_W$ then $\partial Y^\star/\partial\tau > 0$ and $\partial W^\star/\partial\tau > 0$, when $\hat{\tau}_W < \tau < \hat{\tau}$ then $\partial Y^\star/\partial\tau > 0$ and $\partial W^\star/\partial\tau < 0$, when $\tau > \hat{\tau}$ then $\partial Y^\star/\partial\tau < 0$ and $\partial W^\star/\partial\tau < 0$. If $\phi < \alpha$, when $\tau < \hat{\tau}$ then $\partial Y^\star/\partial\tau > 0$ and $\partial W^\star/\partial\tau > 0$, when $\hat{\tau} < \tau < \hat{\tau}_W$ then $\partial Y^\star/\partial\tau < 0$ and $\partial W^\star/\partial\tau > 0$, and when $\tau > \hat{\tau}_W$ then $\partial Y^\star/\partial\tau < 0$ and $\partial W^\star/\partial\tau < 0$.*

Corollary 2 means that the positive impact of a tighter environmental policy on the steady-state output level may have a detrimental impact on the steady-state lifetime welfare if the relative importance of consumption in utility (ϕ) is higher than the relative part of physical capital in output production (α). This leads from the fact that when $\phi > \alpha$ the negative impact of the drag-down effect is greater on lifetime welfare than on final output and the positive impact of the competition for resources effect is lower on lifetime welfare than on final output (see the first and the last terms of the RHS of equations (13) and (11) respectively). As a result, the negative impact of the environmental taxation exceeds the positive impact at a lower value for lifetime welfare than for final output. Therefore, from Proposition 1 and Proposition 3, if $\phi > \alpha$, when $\tau < \hat{\tau}_{\mathrm{W}}$ a tighter environmental policy enhances both the steady-state output level and the steady-state lifetime welfare, when $\hat{\tau}_{\mathrm{W}} < \tau < \hat{\tau}$ a tighter environmental policy enhances the steady-state output level but reduces the steady-state lifetime welfare, and when $\tau > \hat{\tau}$ a tighter environmental policy diminishes both the steady-state output level and the steady-state lifetime welfare.

IV. Social optimum and the optimal environmental taxation

The purpose of this section is to investigate the determinants of the optimal environmental taxation with endogenous investment in individual health and an detrimental impact of pollution on individual health.

In a centralized economy, the central planner aims at maximizing the welfare of the agents, assuming that all generations are symmetric:

$$\max_{\{c_1,c_2,\nu,K,D\}} \log\left(c_1^{\phi}h^{1-\phi}\right)+\theta\log\left(c_2^{\phi}h^{1-\phi}\right),$$

$$s.t.\begin{cases} Y=AK^{\alpha}(\nu L)^{1-\alpha}=Lc_1+Lc_2+D+K, \\ h=\eta(1-\nu)/(\xi S^{\gamma}), \\ S=(E/D)^{\chi}/\mu, \\ E=zY. \end{cases}$$

As demonstrated in Appendix C, consumption at a young and old age are related:[23] $\bar{c}_1=\theta\bar{c}_2$ with $\bar{c}_1=(1-\alpha)\phi\left[A\alpha\phi/\left((1-\alpha)\chi\gamma(1-\phi)+\phi\right)\right]^{1/(1-\alpha)}/\left[\alpha(1+\theta)\right]$. The optimal allocation of time to production is $\bar{\nu}=\phi$ and the optimal stock of physical capital is $\bar{K}=\left[A\alpha\phi/\left((1-\alpha)\chi\gamma(1-\phi)+\phi\right)\right]^{1/(1-\alpha)}\phi L$. Consequently, the optimal final output is $\bar{Y}=A^{1/(1-\alpha)}/\left[\alpha\phi/\left((1-\alpha)\chi\gamma(1-\phi)+\phi\right)\right]^{\alpha/(1-\alpha)}\phi L$. Abatement activity is given by $\bar{D}=\left[(1-\alpha)\chi\gamma(1-\phi)\right]/\left[(1-\alpha)\chi\gamma(1-\phi)+\phi\right]\bar{Y}$ and the optimal stock of pollution in the steady-state is $\bar{S}=\left\{z[(1-\alpha)\chi\gamma(1-\phi)+\phi]/\left[(1-\alpha)\chi\gamma(1-\phi)\right]\right\}^{\chi}/\mu$. Consequently, the optimal value of the environmental tax enabling a decentralized economy to attain the optimal stock of pollution in the steady-state is

$$\bar{\tau}=\frac{(1-\alpha)\chi\gamma(1-\phi)}{(1-\alpha)\chi\gamma(1-\phi)+\phi}. \tag{14}$$

This gives rise to the following proposition.

Proposition 4. *The higher the weight of health in preferences $(1-\phi)$, the elasticity of pollution stock with respect to the net flow of pollution (χ), the detrimental impact of pollution on health (captured by γ) and/or the share of labor in production $(1-\alpha)$; the higher the optimal environmental tax.*

Proof. From equation (14), it is straightforward that $\partial\bar{\tau}/\partial\phi<0$, $\partial\bar{\tau}/\partial\chi>0$, $\partial\bar{\tau}/\partial\gamma>0$ and $\partial\bar{\tau}/\partial\alpha<0$. □

[23] A bar $^{-}$ denotes optimal value.

Nevertheless, an optimal environmental tax is not sufficient to ensure an optimal steady-state equilibrium because in a decentralized economy agents do not internalize the impact of their labor supply decisions on final output and the net flow of pollution. Consequently, they do not supply enough time to output production. To obtain the optimal individual labor supply $\bar{\nu}$, the government has to subsidize health-enhancing activities at a rate (see Appendix D):

$$\bar{\tau^{\nu}} = 1 - \frac{\xi\theta}{(1+\theta)}\left(\frac{z^{\chi}}{\mu}\right)^{\gamma}\left(\frac{(1-\alpha)\chi\gamma(1-\phi)}{(1-\alpha)\chi\gamma(1-\phi)+\phi}\right)^{-\gamma\chi}.$$

The environmental tax $\bar{\tau}$ associated with the subsidy $\bar{\tau^{\nu}}$ makes the steady-state decentralized equilibrium optimal.

V. Extensions

In this section, we extend the previous model in two directions. First, we investigate how our findings about the hump-shaped relation between the environmental taxation and final output in the long-run may be extended to growth, when externalities in physical capital à la Romer (1986) are introduced in the model of sections 2-3. Second, we add the impact of health on productivity, which is well-documented empirically(see the introduction), to investigate how the results of sections 2-3 are affected.

AK endogenous growth

In this section, we consider that external learning by doing à la Romer (1986) exists,[24] such that the productivity scalar $\tilde{A}_t$ evolves as physical capital: $\tilde{A}_t = AK_t^{1-\alpha}$

[24]Following Romer (1986), production factors remain paid at their marginal after environmental tax cost.

to obtain an interest rate independent of physical capital. Consequently, the final output becomes $Y_t = AK_t(\nu_t L)^{1-\alpha}$ and the law of motion of physical capital is given by $K_{t+1} = \theta(1-\alpha)(1-\tau)AK_t(\nu_t L)^{1-\alpha}/(1+\theta)$.

At the steady-state, physical capital and output grow at a constant positive rate $g^\star \equiv K_{t+1}/K_t - 1$, that is, using equation (9)

$$g^\star = \mathcal{A}'(1-\tau)\left[\mathcal{B} + \xi\left(\frac{z^\chi}{\mu}\right)^\gamma \tau^{-\chi\gamma}\right]^{\alpha-1},$$

with $\mathcal{A}' \equiv \theta(1-\alpha)AL^{1-\alpha}\mathcal{B}^{1-\alpha}/(1+\theta)$.

Proposition 5. *Under the assumption of a learning-by-doing source of growth à la Romer (1986), the introduction of endogenous private expenditure in healthcare and the detrimental impact of pollution on health makes the relationship between the BGP growth rate and the environmental tax level is inverted-U shaped. Below (respectively above) an environmental tax-level denoted* $\hat{\tau}_g$ *and defined as:*

$$-\mathcal{B}\hat{\tau}_g^{\chi\gamma} + \xi\left(\frac{z^\chi}{\mu}\right)^\gamma \big((1-\alpha)\chi\gamma(\hat{\tau}_g^{-1}-1)-1\big) = 0, \tag{15}$$

with $\hat{\tau}_g < [1+(1-\alpha)\chi\gamma]^{-1} < 1$*, a tighter environmental taxation raises (respectively lowers) the BGP output growth rate* $g^\star$*.*

Proof. The influence of the environmental taxation on the growth rate at the steady-state is given by

$$\partial g^\star/\partial\tau = \mathcal{A}'\left[\mathcal{B} + \xi\left(\frac{(z/\tau)^\chi}{\mu}\right)^\gamma\right]^{\alpha-2}\tau^{-\chi\gamma}\times \left[-\mathcal{B}\tau^{\chi\gamma} + \xi\left(\frac{z^\chi}{\mu}\right)^\gamma \big((1-\alpha)\chi\gamma(\tau^{-1}-1)-1\big)\right].$$

Consequently $\partial g^\star/\partial\tau > 0$ if the last term in the right-hand side is positive: $-\mathcal{B}\tau^{\chi\gamma} + \xi\left(z^\chi/\mu\right)^\gamma \big((1-\alpha)\chi\gamma(\tau^{-1}-1)-1\big) > 0$. Because the left-hand side of the inequality is a monotonic decreasing function of τ with $\lim\limits_{\tau\to 0} = +\infty$ and $\lim\limits_{\tau\to 1} = -\mathcal{B} - \xi \left(z^{\chi}/\mu\right)^{\gamma} < 0$, there is a unique $\hat{\tau}_g$ defined as $-\mathcal{B}\hat{\tau}_g^{\chi\gamma} + \xi \left(z^{\chi}/\mu\right)^{\gamma} \big((1-\alpha)\chi\gamma(\hat{\tau}_g^{-1} - 1) - 1\big) = 0$, with $\hat{\tau}_g < \left[1 + (1-\alpha)\chi\gamma\right]^{-1} < 1$ (in order for $\hat{\tau}_g$ to exist), such that for $\tau < \hat{\tau}_g$ (respectively $\tau > \hat{\tau}_g$) we have $\partial g^{\star}/\partial\tau > 0$ (resp. $\partial g^{\star}/\partial\tau < 0$). □

Equation (15) defines the environmental tax level $\hat{\tau}_g$ for which its negative influence on the BGP growth rate (the first term in the LHS) equals its positive effect arising from the *competition for resources effect* (the second term in the LHS). For a tax level lower than $\hat{\tau}_g$, the positive impact of the environmental tax is greater than the negative one and an increase in the environmental tax rises the BGP growth rate. Conversely, for a tax level higher than $\hat{\tau}_g$, the *competition for resources effect* is too low for the environmental tax to increase growth.

Health affects labor productivity

As emphasized in the introduction, chronic diseases affect the economy through the huge losses in productivity created. As a result, it is expected that tighter environmental taxation will reduce this productivity loss by reducing pollution and increasing the health-status of workers. To investigate how associating the "productivity effect" with the "competition for resources effect" could further improve the beneficial impact of an environmental policy, we introduce the impact of health on the labor productivity.

We continue to consider that agents in poor health expend more on medical care when they are young and not elderly, following Gutiérrez (2008). In contrast to Williams (2002, 2003), we do not assume that agents in poor health do not work . Rather, we consider that better health-status makes workers more productive and that absenteeism due to illness does not occur.[25] The technology to produce final output becomes $Y_t = A_t K_t^\alpha (h_t^\varepsilon N_t)^{1-\alpha}$ where $\varepsilon \geq 0$ measures the effect of health on labor productivity. The introduction of health-dependent labor productivity leaves the model unchanged except for physical capital accumulation (equation 5): $K_{t+1} = \theta(1-\alpha)(1-\tau)AK_t^\alpha(h_t^\varepsilon \nu_t L)^{1-\alpha}/(1+\theta)$. As a result, the steady-state value of physical capital becomes $K^{\star\star} = \mathcal{A}\ (1-\tau)^{1/(1-\alpha)}\mathcal{V}(\tau)\mathcal{H}(\tau)^\varepsilon$ and the steady-state expression of final output is now $Y^{\star\star} = \mathcal{A}_2\ (1-\tau)^{\alpha/(1-\alpha)}\left(\mathcal{B} + \xi\,(z^\chi/\mu)^\gamma\,\tau^{-\chi\gamma}\right)^{-(1+\varepsilon)}$ with $\mathcal{A}_2 \equiv \mathcal{A}_1\eta^\varepsilon$.

Proposition 6. *When the effect of health on labor productivity is taken into account, the positive effect of an environmental tax on output-level is increased and the tax level at which a tighter environmental tax increases output level is higher. The environmental policy is more likely to increase final output.*

Proof. The tax level, denoted $\hat{\hat{\tau}}$, for which $\partial Y^{\star\star}/\partial\tau = 0$ is defined by

$$(1+\varepsilon)\chi\gamma\xi\left(\frac{z^\chi}{\mu}\right)^\gamma \hat{\hat{\tau}}^{-1} - \frac{\alpha}{1-\alpha}\mathcal{B}\hat{\hat{\tau}}^{\chi\gamma} - \left(\frac{\alpha}{1-\alpha} + (1+\varepsilon)\chi\gamma\right)\xi\left(\frac{z^\chi}{\mu}\right)^\gamma = 0.$$

It is straightforward that for $\varepsilon = 0$, $\hat{\hat{\tau}} = \hat{\tau}$. Furthermore the LHS of the equation increases with ε because $\hat{\hat{\tau}} \in]0,1[$. Therefore from the theorem of implicit function we find that $\partial\hat{\hat{\tau}}/\partial\varepsilon > 0$. Therefore $\hat{\hat{\tau}} > \hat{\tau}$ when $\varepsilon > 0$. □

VI. Conclusion

This article investigates how environmental taxation affects the economy (output-level and -growth, welfare) when the detrimental impact of pollution on health is

[25] We take into account presenteeism, i.e. a worker present but with reduced productivity rather than absenteeism, i.e. a worker absent, because it accounts for not only worker health but also the health of their family. For the US in 2003, Davis et al. (2005) estimated that 55 million workers out of 148 million workers, ages 19 to 64, reported an inability to concentrate at work because of their own illness or that of their family.

taken into account and working-age individuals have to invest in healthcare to limit this impact. It demonstrates that, in a two-period overlapping generations model, the relationship between environmental taxation and economic activity (output level and output growth) is inverted-U shaped. This inverted-U shaped relationship between the environmental tax and economic activity is due to a positive effect arising from the competition for resources between the final output sector and the health-care sector that offsets the detrimental "*drag-down effect*" for low values of the environmental tax. Thus, a tighter environmental tax is more likely to increase (rather than decrease) output-level and -growth when: health is very pollution-sensitive, the weight of health in preferences is high, the polluting capacity of the production technology is high, and the rate of natural purification of pollutants is low. Furthermore, when the productivity effect of better health status is taken into account, the environmental tax is more likely to promote final output. This article also demonstrates that the link between environmental taxation and lifetime welfare is inverted-U shaped and that a tighter environmental policy may enhance economic activity while reducing steady-state lifetime welfare. Finally it investigates the social optimum and the determinants of the optimal environmental tax.

The main policy implication of our findings is the need to continue and reinforce efforts to reduce pollution, for example in economies like China and other Asian countries (Malaysia, Vietnam, etc.), where the detrimental effects of pollution on health are the highest and are predicted to increase significantly; where production processes generate high pollution emissions; and the health-sector is not efficient. Even in the high-income countries of North America and Europe, where production is less polluting and healthcare spending more efficient, efforts to curb pollution should be pursued and strengthened, O.E.C.D. (2008) forecasting that pollution emissions will continue to rise in the future with increasing negative effects on health. In both cases, there would be a greater scope for individual health-status improvements through a tighter environmental policy, and our results suggest that the expected positive impacts of such a policy would more than offset the detrimental ones. Nevertheless, our results also highlight that the welfare implications of any environmental policy should be carefully taken into account to avoid the situation where there is a negative impact on welfare from the environmental taxation while economic activity is increased.

This article also highlights the need for further investigation of the link between the environment, health and economic activity. Indeed, a simple two-period overlapping-generations framework does not capture all the implications of an important feature of the chronic disease: its persistent effect over decades. This has major implications in terms of social security funding (see introduction) and intergenerational redistribution. It could also impact the long-term behaviour of the agents, not only in terms of leisure, but also in terms of consumption ("brown" and "green" consumption), and in terms of time preferences. This could, in turn, reinforce the expected positive effects of the environmental policy, in terms of both output (-level and -growth) and lifetime welfare. Such a potential and persistent influence of tighter environmental policy on health appears a promising area of empirical and theoretical investigation.

References

Agénor, P.-R. (2008). Health and infrastructure in a model of endogenous growth. *Journal of Macroeconomics*, 30(4):1407–1422.

Agnani, B., Iza, A., and Gutierrez, M. (2005). Growth in overlapping generation economies with non-renewable resources. *Journal of Environmental Economics and Management*, 50(2):300–318.

Aisa, R. and Pueyo, F. (2004). Endogenous longevity, health and economic growth: a slow growth for a longer life? *Economics Bulletin*, 9(3):1–10.

Bednarek, H. L., Pecchenino, R. A., and Stearns, S. C. (2008). Do your neighbors influence your health? *Journal of Public Economic Theory*, 10(2):301–315.

Briggs, D. (2003). Environmental pollution and the global burden of disease. *British Medical Bulletin*, 68(1):1–24.

Brook, R., Franklin, B., Cascio, W., Hong, Y., Howard, G., Lipsett, M., Luepker, R., Mittleman, M., Samet, M., Smith, S., and Tager, I. (2004). Air pollution and cardiovascular disease: a statement for healthcare professionials from the expert panel on population and prevention science of the american heart association. *Circulation*, 109:26655–2671.

Cropper, M. (1981). Measuring the benefits from reduced morbidity. *The American Economic Review*, 71:235–240.

Davis, K., Collins, S., Doty, M., Ho, A., and Holmgren, A. (2005). Health and productivity amoung u.s. workers. Issue brief, The Commonwealth Fund.

De La Croix, D. and Michel, P. (2002). *A Theory of Economic Growth : dynamics and policy in overlapping generations*. Cambridge University Press.

Devol, R. and Bedroussian, A. (2007). An unhealthy america: The economic burden of chronic disease – charting a new course to save lives and increase productivity and economic growth. Technical report, Milken Institute.

Diamond, P. (1965). National debt in a neoclassical growth model. *American Economic Review*, 55:1126–1150.

Dormont, B., Grignon, M., and Huber, H. (2006). Health expenditure growth: Reassessing the threat of ageing. *Health Economics*, 15(9):947–963.

Dormont, B., Martins, J., Pelgrin, F., and Suhrcke, M. (2007). Health expenditures, longevity and growth. Technical report.

Gradus, R. and Smulders, S. (1993). The trade-off between environmental care and long-term growth-pollution in three prototype growth models. *Journal of Economics*, 58(1):25–51.

Gradus, R. and Smulders, S. (1996). Pollution abatement and long-term growth. *European Journal of Political Economy*, 12:505–532.

Grossman, M. (1972). On the concept of health capital and the demand for health. *Journal of Political Economy*, 80:223–255.

Gutiérrez, M. (2008). Dynamic inefficiency in an overlapping generation economy with pollution and health costs. *Journal of Public Economic Theory*, 10(4):563–594.

John, A. and Pecchenino, R. (1994). An overlapping generations model of growth and the environment. *The Economic Journal*, 104:1393–1410.

John, A., Pecchenino, R., Schimmelpfenning, D., and Schreft, S. (1995). Short-lived agents and the long-lived environment. *Journal of Public Economics*, 58:127–141.

Jouvet, P., Pestieau, P., and Ponthière, G. (2010). Longevity and environmental quality in an olg model. *Journal of Economics*, 100(3):191–216.

Kemp, M. and Long, N. (1979). The under-exploitation of natural resources: A model with overlapping generations. *Economic Record*, 55:214–221.

Lang, A., Galloway, T., Scarlett, A., Henley, W., Depledge, M., Wallace, R., and Melzer, D. (2008). Association of urinary bisphenol a concentration with medical disorders and laboratory abnormalities in adults. *The Journal of the American Medical Association*, 300(11):1303–1310.

Lee, D.-H., Lee, I.-K., Jin, S.-H., Steffes, M., and Jocbs, D. (2007). Association between serum concentrations of persistent organic pollutants and insulin resistance among nondiabetic adults: results from the national health and nutrition examination survey. *Diabetes Care*, 30:622–628.

Mariani, F., Perez-Barahona, A., and Raffin, N. (2009). Life expectancy and the environment. Iza discussion paper 4564.

Mourmouras, A. (1991). Competitive equilibria and sustainable growth in a life-cycle model with natural resources. *Scandinavian Journal of Economics*, 93(4):585–591.

Mourmouras, A. (1993). Conservationist government policies and intergenerational equity in an overlapping generations model with renewable resources. *Journal of Public Economics*, 51(2):249–268.

Mullahy, J. and Robert, S. (2008). No time to lose? time constraints and physical activity. Technical report, NBER Working Paper 14513.

O.E.C.D. (2008). *OECD Environmental Outlook to 2030*. Organisation for Economic Co-operation and Development, Paris.

Oueslati, W. (2002). Environmental policy in an endogenous growth model with human capital and endogenous labor supply. *Economic Modelling*, 19:487–507.

Pautrel, X. (2008). Reconsidering the impact of pollution on long-run growth when pollution influences health and agents have a finite-lifetime. *Environmental and Resource Economics*, 40(1):37–52.

Pautrel, X. (2009a). Health-enhancing activities and the environment: How competing time allocations make the environmental policy beneficial. Nota di lavaro 111.2009, Fondazione Eni Enrico Mattei.

Pautrel, X. (2009b). Pollution and life expectancy: How environmental policy can promote growth. *Ecological Economics*, 68(4):1040–1051.

Rajagopalan, S., Sun, Q., and Chen, L. C. (2005). Particulate pollution and endothelial function: Déjà vu all over again in the air. *Circulation*, 111(2869-2871).

Romer, P. (1986). Increasing returns and long run growth. *Journal of Political Economy*, 94:1002–1037.

Russell, L., Ibuka, Y., and Abraham, K. (2007). Health-related activities in the american time use survey. *Medical Care*, 45(7):680–685.

Skinner, S., Fisher, E., and Wenberg, J. (2001). The efficiency of medicare. National Bureau of Economic Researh Working paper 8395, National Bureau of Economic Research.

Suhrcke, M., Mckee, M., Stuckler, D., Arce, R., Tsolova, S., and Mortensen, J. (2006a). The contribution of health to the economy in the european union. *Public Health*, 120:994–1001.

Suhrcke, M., Nugent, R., Stuckler, D., and Rocco, L. (2006b). Chronic disease: An economic perspective. Technical report, Oxford Health Alliance, London.

van Zon, A. and Muysken, J. (1997). Health, education and endogenous growth. Technical Report 97-009, MERIT Research Memorandum.

van Zon, A. and Muysken, J. (2001). Health and endogenous growth. *Journal of Health Economics*, 20:169–185.

Varvarigos, D. (2008). Environmental quality, life expectancy and sustainable economic growth. Working paper 08/19, University of Leicester, Departement of Economics.

WHO (2004). The global burden of disease: 2004 update. Technical report, World Health Organization.

WHO (2005). Preventing chronic diseases: A vital investment (who, geneva, 2005). Technical report, World Health Organization, Geneva.

Williams, R. (2002). Environmental tax interactions when pollution affects health or productivity. *Journal of Environmental Economics and Management*, 44(2):261–270.

Williams, R. (2003). Health effects and optimal environmental taxes. *Journal of Public Economics*, 87:323–335.

Xepapadeas, A., Mäler, K.-G., and Vincent, J. R. (2005). *Chapter 23 Economic growth and the environment*, volume Volume 3, pages 1219–1271. Elsevier.

Zhang, X., Zhao, X., and Harris, A. (2008). Chronic diseases and labour force participation in australia. *Journal of Health Economics*.

Appendix

A Influence of the environmental tax on the steady-state output in competitive equilibrium

The influence of environmental tax on the steady-state level of output is given by:

$$\partial Y^\star/\partial\tau = Y^\star\tau^{-\gamma\chi}(1-\tau)^{-1}\left(\mathcal{B}+\xi\left(\frac{z^\chi}{\mu}\right)^\gamma\tau^{-\chi\gamma}\right)^{-1}\times \left[\chi\gamma\xi\left(\frac{z^\chi}{\mu}\right)^\gamma\tau^{-1}-\frac{\alpha}{1-\alpha}\mathcal{B}\tau^{\chi\gamma}-\left(\frac{\alpha}{1-\alpha}+\chi\gamma\right)\xi\left(\frac{z^\chi}{\mu}\right)^\gamma\right].$$

The influence of environmental tax on the steady-state level of output is positive if

$$-\frac{\alpha}{1-\alpha}\mathcal{B}\tau^{\chi\gamma}+\xi\left(\chi\gamma(\tau^{-1}-1)-\frac{\alpha}{1-\alpha}\right)\left(\frac{z^\chi}{\mu}\right)^\gamma>0. \tag{A.1}$$

Because the left-hand side of the inequality is a decreasing monotonic function of τ with $\lim_{\tau\to 0} = +\infty$ and $\lim_{\tau\to 1} = -\left[\alpha/(1-\alpha)\right]\left(\mathcal{B}+\xi\left(z^\chi/\mu\right)^\gamma\right) < 0$, there is a unique $\tau \in]0,1]$ under which the inequality is verified. This is denoted $\hat{\tau}$ and is defined by $-\alpha\mathcal{B}\hat{\tau}^{\chi\gamma}/(1-\alpha)+\xi\left(\chi\gamma(\hat{\tau}^{-1}-1)-\alpha/(1-\alpha)\right)(z^{\chi}/\mu)^{\gamma}=0$ with $\hat{\tau}<(1-\alpha)\chi\gamma/((1-\alpha)\chi\gamma+\alpha)<1$ for the second term in the LHS being positive, that is to obtain a solution for $\hat{\tau}$. For $\tau<\hat{\tau}$ (respectively $\tau>\hat{\tau}$), we have $\partial Y^{\star}/\partial\tau>0$ (respectively $\partial Y^{\star}/\partial\tau<0$). When $\gamma=0$, the left-hand side of the inequality is independent of τ and negative, therefore we have $\partial Y^{\star}/\partial\tau<0$. When $\xi=0$, the condition (A.1) is never verified whatever $\tau>0$ and therefore $\partial Y^{\star}/\partial\tau<0$

B Influence of the environmental tax on steady-state lifetime welfare in competitive equilibrium

The lifetime welfare along the BGP is defined by the lifetime utility function (1) evaluated along the BGP. That is, using equations (2), (3), (4), (8), (9), (10) and $Y^{\star}=(1+\theta)K^{\star}/\left[\theta(1-\alpha)(1-\tau)\right]$, we obtain $W^{\star}=(1+\theta)\log\Omega(\tau)$ with

$$\Omega(\tau)\equiv\left(\frac{1-\alpha}{1+\theta}\mathcal{A}_1\eta^{-1}\right)^{\phi}(1-\tau)^{\frac{\phi}{1-\alpha}}\left[\mathcal{B}+\xi\left(\frac{z^{\chi}}{\mu}\right)^{\gamma}\tau^{-\chi\gamma}\right]^{-1}$$

and $\mathcal{A}_1\equiv\mathcal{B}(1+\theta)\left((1-\alpha)(\theta/(1+\theta))A\right)^{1/(1-\alpha)}L/\left[\theta(1-\alpha)\right]$. Furthermore $\partial W^{\star}/\partial\tau=\left[(1+\theta)/\Omega(\tau)\right]\times\partial\Omega(\tau)/\partial\tau$ with

$$\begin{aligned}\frac{\partial\Omega(\tau)}{\partial\tau}=&\left(\frac{1-\alpha}{1+\theta}\mathcal{A}_1\eta^{-1}\right)^{\phi}\left[\mathcal{B}+\xi\left(\frac{z^{\chi}}{\mu}\right)^{\gamma}\tau^{-\chi\gamma}\right]^{-2}(1-\tau)^{\frac{\phi}{1-\alpha}-1}\tau^{-\chi\gamma}\times\\&\left\{-\frac{\phi}{1-\alpha}\mathcal{B}\tau^{\chi\gamma}+\xi\left(\frac{z^{\chi}}{\mu}\right)^{\gamma}\left[\chi\gamma\left(\tau^{-1}-1\right)-\frac{\phi}{1-\alpha}\right]\right\}.\end{aligned}\tag{B.1}$$

Therefore, $\partial W^{\star}/\partial\tau>0$ if $\partial\Omega(\tau)/\partial\tau>0$, that is from (B.1), if $-\phi\mathcal{B}\tau^{\chi\gamma}/(1-\alpha)+\xi\left(z^{\chi}/\mu\right)^{\gamma}\left[\chi\gamma\left(\tau^{-1}-1\right)-\phi/(1-\alpha)\right]>0$. Because the left-hand side of the inequality is a monotonic decreasing function of τ with $\lim_{\tau\to 0}=+\infty$ and $\lim_{\tau\to 1}=-\phi\left[\mathcal{B}+\xi\left(z^{\chi}/\mu\right)^{\gamma}\right]/(1-\alpha)<0$, there is a unique $\tau\in]0,1]$ under which the inequality is verified. This is denoted $\hat{\tau}_{\mathrm{W}}$ and is defined as: $-\phi\mathcal{B}\hat{\tau}_{\mathrm{W}}^{\chi\gamma}/(1-\alpha)+$

$\xi \left(z^{\chi}/\mu\right)^{\gamma} \left[\chi\gamma\left(\hat{\tau}_{\mathrm{w}}^{-1}-1\right)-\phi/(1-\alpha)\right] = 0$ with $\hat{\tau}_{\mathrm{w}} < \left[1+\phi/((1-\alpha)\chi\gamma)\right]^{-1} < 1$. When $\tau < \hat{\tau}_{\mathrm{w}}$ (respectively $\tau > \hat{\tau}_{\mathrm{w}}$), we have $\partial W^{\star}/\partial\tau > 0$ (respectively $\partial W^{\star}/\partial\tau < 0$).

C The optimum

In a centralized economy, the central planner aims at maximizing the welfare of the agents, assuming that all generations are symmetric:

$$\max_{\{c_1,c_2,\nu,K,D\}} \log\left(c_1^{\phi}h^{1-\phi}\right)+\theta\log\left(c_2^{\phi}h^{1-\phi}\right),$$

$$s.t. \begin{cases} F(K,\nu,L)=\tilde{A}K^{\alpha}(\nu L)^{1-\alpha}=Lc_1+Lc_2+D+K, \\ h=\eta(1-\nu)/(\xi S^{\gamma}), \\ S=(E/D)^{\chi}/\mu, \\ E=zY. \end{cases}$$

The Lagrangian may be written as:

$$\mathcal{L}=\phi\left(\log c_1+\theta\log c_2\right)+(1+\theta)(1-\phi)\left(\chi\gamma\log D-\chi\gamma\log F(K,\nu,L)+\log(1-\nu)\right)$$
$$+(1+\theta)(1-\phi)\log\frac{\eta\mu^{\gamma}}{\xi z^{\gamma\chi}}+\lambda\left(F(K,\nu,L)-Lc_1-Lc_2-D-K\right).$$

First-order conditions are

$$\phi c_1^{-1}=\lambda L=\theta\phi c_2^{-1}, \tag{C.1}$$

that is $c_2=\theta c_1$ and

$$\lambda(F_K'(\cdot)-1)=(1+\theta)\chi\gamma(1-\phi)F_K'(\cdot)/F(\cdot), \tag{C.2}$$

$$(1-\phi)(1+\theta)\left(\gamma\chi F_{\nu}'(\cdot)/F(\cdot)+(1-\nu)^{-1}\right)=\lambda F_{\nu}'(\cdot), \tag{C.3}$$

$$\lambda=(1+\theta)\chi\gamma(1-\phi)D^{-1}. \tag{C.4}$$

Equations (C.2) and (C.4) give $D = Y(1 - 1/F'_K(\cdot)) = Y - \alpha^{-1}K$ and from (C.1), we obtain $\lambda = \phi/(c_1 L)$. Therefore $D = \phi^{-1}(1+\theta)\chi\gamma(1-\phi)c_1 L$ and consequently the market equilibrium gives $Y = c_1 L(1+\theta)\left[1 + \phi^{-1}\chi\gamma(1-\phi)\right] + K$ that is

$$c_1 L = \frac{Y - K}{(1+\theta)\left[1 + \phi^{-1}\chi\gamma(1-\phi)\right]}.$$

In the same way, the market equilibrium may be written as $Y = (1+\theta)c_1 L + K + Y - \alpha^{-1}K$ that is $(1+\theta)c_1 L = (\alpha^{-1} - 1)K$. Consequently $Y - K = (\alpha^{-1} - 1)\left[1 + \phi^{-1}\chi\gamma(1-\phi)\right] K$ that is

$$Y = \alpha^{-1}\phi^{-1}\left[(1-\alpha)\chi\gamma(1-\phi) + \phi\right] K. \tag{C.5}$$

Finally, equation (C.3) gives $(1-\phi)(1+\theta)\left((1-\alpha)\gamma\chi + \nu/(1-\nu)\right) = \phi(1+\theta)\alpha Y/K$ that is $\nu = \phi$. From (C.5), $\bar{K} = \left[A\alpha\phi/((1-\alpha)\chi\gamma(1-\phi)+\phi)\right]^{1/(1-\alpha)}\phi L$, $\bar{Y} = A^{1/(1-\alpha)}\left[\alpha\phi/\left((1-\alpha)\chi\gamma(1-\phi)+\phi\right)\right]^{\alpha/(1-\alpha)}\phi L$, $\bar{D} = [(1-\alpha)\chi\gamma(1-\phi)]/[(1-\alpha)\chi\gamma(1-\phi)+\phi]\bar{Y}$ and $\bar{c}_1 = (1-\alpha)\left[A\alpha\phi/\left((1-\alpha)\chi\gamma(1-\phi)+\phi\right)\right]^{1/(1-\alpha)}\phi/\left[\alpha(1+\theta)\right]$.

D Subsidy to health-enhancing activities

The competitive equilibrium is rewritten assuming that the government subsidises agents' health-enhancing activities by paying a subsidy, τ^ν, towards the opportunity cost of health-enhancing activities (i.e. the foregone wage $(1-\nu_t)w_t$). This is funded by a lump-sum tax denoted a_t. The budget-constraint for the young agent born at period t becomes $c_1 + s_t + a_t = \nu_t w_t + \tau^\nu(1-\nu_t)w_t$. The maximization of lifetime utility gives $s_t = \theta(\nu_t w_t + \tau^\nu(1-\nu_t)w_t - a_t)/(1+\theta)$ and because government budget constraints require $a_t = \tau^\nu(1-\nu_t)w_t$, we obtain $s_t = \theta\nu_t w_t/(1+\theta)$ and the individual labor supply is $\nu_t = (1+\theta)\phi(1-\tau^\nu)h_{t+1}/\left[\theta(1-\phi)\right]$.

In the steady-state equilibrium, $h^\star$ and $v^\star$ are similar to (8) and (9) with the term $(1+\theta)/\theta$ replaced by $(1-\tau^\nu)(1+\theta)/\theta$. The subsidy of health-enhancing activities that enables replication of the optimal allocation of time between health-enhancing activities and production (denoted $\bar{\tau^\nu}$) is such that $\nu^\star = \phi$, that is

$$\bar{\tau^\nu} = 1 - \frac{\xi\theta}{(1+\theta)} \left(\frac{z^\chi}{\mu}\right)^\gamma \left(\frac{(1-\alpha)\chi\gamma(1-\phi)}{(1-\alpha)\chi\gamma(1-\phi)+\phi}\right)^{-\gamma\chi}.$$