Reassessing the effects of environmental taxation when pollution affects health over the life-cycle *

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Abstract

We introduce the link between pollution, morbidity and productivity over the life-cycle in a two-period overlapping generations model. As the environmental tax improves the health-profile over the life-cycle, it influences saving, investment in health, labor supply and retirement. As a result, we identify effects of environmental taxation beyond the standard crowding-out and productivity effects captured by the past literature. We show that whether those effects are positive or negative for the economy crucially depends on the degree of substitutability between young and old labor. Our numerical examples suggest that that those new effects alleviate the negative effects of environmental taxation on output and decrease potential positive welfare effects.

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1 Introduction

What is the economic effect of environmental taxation when pollution affects morbidity? Past contributions have addressed this question without accounting for the effect of pollution on health over the life-cycle. By contrast, we build a two-period overlapping generations model, which captures the link between pollution, morbidity and productivity over the life-cycle. We contribute to the theoretical literature by identifying new effects of environmental taxation on the economy, and we provide numerical simulations to assess the magnitude of those effects.

The effect of pollution on morbidity is well established in the epidemiological literature. Pollution is known as a causal factor for certain chronic diseases, especially cancer, cardiovascular disease and respiratory diseases, that have durable detrimental impacts in terms of illness and disability.[1] According to Briggs (2003) about 8-9% of the total disease burden may be attributed to pollution in developed countries. While direct and indirect impacts of illness on productivity is the object of growing interest,[2] the overall fraction of pollution-related health problems that affect productivity is unknown. Nevertheless, the empirical literature focuses on some specific types of pollution and finds that the negative effect of pollution on productivity is quantitatively significant. Hausman et al. (1984) estimate that a 1 unit ($\mu g/m^3$) increase in particulate matter pollution increases lost work days by 0.7%. Hansen and Selte (2000) show that sick leaves are significantly linked to particulate matter pollution (PM10). Hanna and Oliva (2011) find that a one percent increase in sulfur dioxide results in a 0.61 percent decrease in the hours worked in Mexico city. Graff Zivin and Neidell (2012) find that a 10 ppb decrease in Ozone concentrations increases worker productivity by 4.2%. With respect to the effect of outdoor air pollution on the productivity of indoor workers, Chang et al. (2014)

[1] See Brauer et al. (2011), Ruckerl et al. (2011), Gold and Mittleman (2013), Rajagopalan and Brook (2012), Brook et al. (2010) regarding air pollution; Paulu et al. (1999), Valent et al. (2004) for water pollution and Nadal et al. (2004), Chen and Liao (2005), Schuhmacher and Domingo (2006) for industrial pollution.

[2] See Bloom et al. (2004), Devol and Bedroussian (2007) and Zhang et al. (2011), for example.

"suggest that nationwide reductions in PM2.5 from 1999 to 2008 generated $19.5 billion in labor cost savings, which is roughly one-third of the total welfare benefits associated with this change."

Thus, the theoretical literature has explored the effect of environmental policy taking into consideration the link between pollution and health in infinite horizon models, with the idea that productivity gains and decreased medical expenditure related to pollution reduction generally mitigate the costs of environmental policies (See Mayeres and Van Regemorter (2008), Huhtala and Samakovlis (2007), and Ostblom and Samakovlis (2007)). Williams (2002) proposes a general equilibrium model in which reduced pollution increases health or productivity. In contrast to the previously cited studies, this author finds that the resulting effects on labor supply can magnify or diminish the benefits of reduced pollution. Williams (2003) further shows that interactions with health effects from pollution reduce the optimal environmental tax rather than increasing it as in Schwartz and Repetto (2000). In a growth model with research and development, Aloi and Tournemaine (2011) find that environmental taxation has a positive effect on growth and welfare through productivity gains and reallocation of resources toward R&D.

Those models ignore the interactions between pollution, morbidity, and productivity over the life-cycle, thereby missing some of the channels through which environmental policy affects the economy. There is however empirical evidence that the health profile is susceptible to modification by pollution. Indeed, pollution contributes to chronic diseases, which primarily affect people age 15 to 59 according to the WHO. There is also empirical evidence that the health profile influences the productivity profile (Lakdawalla et al. 2004, Bhattacharya et al. 2008, Perlkowski and Berger 2004). Furthermore, the empirical literature indicates that the health profile is internalized and weights in life-cycle saving, labor and retirement (Dwyer and Mitchell 1999, Deschryvere 2006, amongst others). Additionally , as pointed out by Cropper (1981), individuals' investment in health during the first part of their lives interacts with pollution, which modifies their health profile. Thus, a decreased investment in health can potentially offset some of the benefits of environmental taxation on health.

Therefore, we propose to study the effects of environmental taxation in a two-period overlapping generations model which captures the link between pollution, morbidity and productivity over the life-cycle. Our model includes the following new features. First, we explicitly model the health status as a stock that increases with investment in health and decreases with pollution. Second, we make the link between health and productivity over the life-cycle explicit: Efficient labor is a function of health status and hours worked. Third, we model retirement decisions, allowing individuals to choose whether to continue to work or to retire during the second stage of their lives. Fourth, while past overlapping generations models generally assume perfect substitution between young and old workers, our model allows for labor by the young and the old to be complements or substitutes. Indeed, young and old workers' skills are not perfect substitutes. The literature on economic growth finds that young and old workers' comparative advantage in different complementary tasks explains why convergence is not instantaneous (Kremer and Thomson 1998). The analysis of pension reforms and their effect on youth employment shows that employment of old workers is positively correlated to employment of young workers (Börsch-Supan and R. 2010, Gruber et al. 2010, Kalwij et al. 2010). Furthermore, only a few empirical contributions have estimated the elasticities of substitution or complementarity between age groups and there is no clear consensus in the empirical literature on whether workers of different ages are complements or substitutes as skills and age are closely related. Murphy and Welch (1992) find complementarity between young and old workers within or outside the same education group and Hebbink (1993) finds that workers of different age groups are complements. Card and Lemieux (2001) find that for both high school and college educated workers from different age groups are imperfect substitutes, and Ottaviano and Peri (2012) estimate that workers within the same education group but different levels of experience are imperfect substitutes. Additionally, it seems important to allow for substitutability or complementarity between young and old workers in light of the recent life-cycle literature, which shows that accounting for complementarity may influence policy outcomes (Cassou et al. 2013, Imrohoroglu and Kitao 2009). Finally, we model investment in health as time individuals derive from leisure rather than as an amount they spend on health services. Accounting for investment in health in the form of both time and expenditure would render the model intractable. Whereas the past literature focused on health expenditure, a contribution of our paper is to focus on time invested in health, which is an important factor in health outcomes. Additionally, time investment in health is also particularly relevant to study in a life-cycle framework which accounts for substitution between young and old labor. Our modeling choice is also justified by the fact that, in publicly financed health care systems, health care spending is not an important source of income uncertainty and does not significantly influence the consumption-saving choice of individuals (Domeij and Johannesson 2006, Chou et al. 2003). Independent of the health care system, another justification for this modeling choice comes from the empirical literature on the determinants of health. Cawley and Ruhm (2011a;b) point out that the determinants of health include medical care, time investment and the environment. "However, in industrialized countries where morbidity and mortality are primarily related to chronic rather than infectious diseases, health behaviors are particularly important." Furthermore, Folland et al. (2013) find that health care consumption expenditure does not result in better health whereas lifestyle choices matter. The empirical literature suggests that time spent on activities such as sleeping, diet and physical exercise, smoking, or drinking is an important factor in health outcomes (Contoyannis and Jones 2004, Mullahy and Robert 2008; 2010, Xu 2010; 2013, and the 2008 Physical Activity guidelines for Americans edited by the US department of Health and Human services). Thus, while the past literature focused on preventive health expenditure, we focus on time investment in health as an important form of prevention. Additionally, in the same way as preventive health expenditure decreases as individuals age (Cropper 1977), empirical evidence shows that lifestyle choices are concentrated on working years. For example, the 2008 US Time Use Survey indicates that 80.3% of individuals practicing sports and exercise are age 15-54. Thus, our model assumes that preventive time investment in health is done by the young and that the benefits of this investment are reaped by the old.[3] Therefore, our health investment function accurately captures characteristics of investment in health that matters for health outcomes.

Our work fills a void in the overlapping generations literature. Indeed, Pautrel (2012) assumes a constant health profile. Mathieu-Bolh and Pautrel (2011) and Raffin (2012) assume an ad-hoc link between pollution and productivity and do not model health. Furthermore, in those articles, the age-productivity profile is not internalized by individuals.[4] Last, neither those past contributions allow individuals to choose between work or retirement in the second period of their lives, nor they explore various characteristics of young and old labor. By contrast, we model the link between pollution, health and productivity over the life-cycle. We show that when individuals internalize changes in the health profile, environmental taxation yields new effects. The main results of the paper are as follows.

1. We provide a decomposition of the effects of the environmental taxation on output and identify new effects. A first new effect is the "health-saving effect" describing changes in saving. The environmental tax limits the decline in health over the life-cycle and modifies investment in health. Changes in the health profile are internalized and modify the efficient wage profile, which triggers changes in saving. The efficient wage profile is modified in different ways depending on the complementarity or substitutability of labor across periods of life. As a result, when old and young labor are substitutes (complements), the health-saving effect is negative (positive). We show that if the life-cycle characteristic of the health

[3] There is no investment in health in the second stage of life because individuals die at the end of the second stage. Furthermore, empirical evidence indicates that in the second stage of life, the nature of health expenditure changes from preventive toward curative (Ozkan 2011).

[4] In Mathieu-Bolh and Pautrel (2011), the exogenous age-productivity profile only influences aggregate variables through intergenerational redistribution. By contrast, in our framework, health and retirement decisions are internalized. Thus environmental taxation influences the health profile, individual decisions, and thereby the aggregate economy.

profile is ignored and investment in health is exogenous, the health-saving effect disappears.

2. Our model captures the effects of environmental taxation on aggregate efficient labor. When time investment in health changes, it triggers changes in labor supply decisions. Two new effects appear, the “young labor effect" and the “retirement effect". Those effects modify the response of aggregate efficient labor. This result is in sharp contrast with much of the existing literature, which generally assumes that environmental taxation has a negative effect on output (crowding-out effect) and only positively impacts aggregate efficient labor through workers' productivity (productivity effect). Furthermore, we show that new labor supply effects of environmental taxation on output also crucially depend on the degree of substitutability between old and young labor.

3. Our numerical simulations of the model suggest that those new effects alleviate the negative effect of an increase in environmental taxation on output and decrease potential welfare effects.

The paper is organized as follows. In section two, we present the model. In section three, we describe the steady state and discuss our results. In section four, we present numerical examples.

2 The economy

We consider an infinite horizon economy where agents live two periods. Population is assumed to be constant and is equal to $2N$.

2.1 Individuals

Individuals work during the two periods of their lives. Each young agent is endowed with one unit of time, supplying $\lambda_{1,t} \in]0,1[$ in final production, using $m_t \in]0,1[$ as an investment in healthcare activities to improve her health status in the second period of her life, and using the remaining time $1 - m_t - \lambda_{1,t}$, as leisure. Therefore, when young, she earns a wage income $\lambda_{1,t} w_{1,t}$, where $w_{1,t}$ is the efficient wage. This income is used to consume $c_{1,t}$, to save s_t or to pay retirement benefits ($\tau_t^w w_{1,t}$ with $\tau_t^w \in (0,1)$):

$$(1 - \tau_t^w)\lambda_{1,t} w_{1,t} = c_{1,t} + s_t \tag{1}$$

During the second period, each agent is also endowed with one unit of time, supplying $\lambda_{2,t+1} \in (0,1)$ in final production and the remaining time $1-\lambda_{2,t+1}$ as retired. When old, she earns a wage income $\lambda_{2,t+1} w_{2,t+1}$. She also receives the revenue of her first period saving and retirement benefits q_{t+1}. Therefore, her second period consumption is:

$$c_{2,t+1} = R_{t+1} s_t + (1 - \tau_{t+1}^w) w_{2,t+1} \lambda_{2,t+1} + (1 - \lambda_{2,t+1}) q_{t+1}$$

with $R_{t+1} \equiv 1 + r_{t+1}$. Assuming a pay-as-you-go system, the retirement benefits paid to retirees in t must be equal to the contributions by workers (who include the old born in t and the young born in $t+1$):

$$(1 - \lambda_{2,t+1}) q_{t+1} = \tau_{t+1}^w \left[\lambda_{2,t+1} w_{2,t+1} + \lambda_{1,t+1} w_{1,t+1}\right]$$

Therefore the budget constraint of an old agent born in t is :

$$c_{2,t+1} = R_{t+1} s_t + \left[\lambda_{2,t+1} w_{2,t+1} + \tau_{t+1}^w \lambda_{1,t+1} w_{1,t+1}\right] \tag{2}$$

Individuals are born in period t with a health-status denoted $h_{1,t}$. The health status of an agent born in t evolves between period t and period $t+1$ depending on two opposing forces (Aisa and Pueyo 2004). On one hand, the health status improves with the investment m_t made by the young agent. On the other hand, biological processes involve a natural decay in health as time goes by (Grossman 1972). Following Cropper (1981), we also assume that health depreciates over time as a function of the stock of pollution (denoted P_t). Therefore, for an agent born in t, the individual health-status evolves from period t to period $t+1$ according to:

$$h_{2,t+1} - h_{1,t} = H(m_t) - d\left(P_t\right)\ h_{1,t} \tag{3}$$

with $H'(m_t) > 0$, $H''(m_t) < 0$. Therefore, investment in health makes the health profile steeper. The detrimental influence of pollution on health appears in the depreciation rate function $d(P_t) \in]0,1[$ with $d'(P_t) > 0$.[5]

The lifetime utility of the representative agent born in t is:

$$U_t = \log\left(\left(c_{1,t}(1-m_t-\lambda_{1,t})^{\varphi}\right)^{\phi} h_{1,t}^{1-\phi}\right) + \beta \log\left(\left(c_{2,t+1}(1-\lambda_{2,t+1})^{\gamma}\right)^{\phi} h_{2,t+1}^{1-\phi}\right) \quad (4)$$

β is the time-preference parameter, φ captures the preference for leisure by the young and γ captures the preference for leisure by the old (or retirement). The parameter $\phi \in (0,1)$ captures the influence of the health-status in utility.

The maximization of (4) subject to (1), (2) and (3) yields saving:

$$s_t = \frac{\beta(1-\tau_t^w)\lambda_{1,t}w_{1,t} - \left[\lambda_{2,t+1}w_{2,t+1} + \tau_{t+1}^w \lambda_{1,t+1}w_{1,t+1}\right]/R_{t+1}}{1+\beta}, \quad (5)$$

Saving reflects the difference between the after-tax income available in the economy in the first period and the present value of income in the second period. In the first period, the after tax income represents the income of the young. In the second period, it represents the income of the old, which encompasses labor and retirement income. Retirement income is proportional to the time retirees spent working while they were young. The later the old retire (λ_2 high), the higher their income and the lower their saving.

In the presence of a PAYG system, the old receive retirement benefits whereas the young pay retirement contributions. Intergenerational redistribution that takes place through the PAYG influences the saving rate. Contributions to the retirement system are influenced by the choice of labor versus investment in health by the young.

Utility maximization also give labor supplied by the young in final output:

$$\lambda_{1,t} = \frac{(1+\beta)(1-m_t)}{1+\beta+\varphi} - \frac{\varphi\left[\lambda_{2,t+1}\frac{w_{2,t+1}/R_{t+1}}{w_{1,t}} + \tau_{t+1}^w \lambda_{1,t+1}\frac{w_{1,t+1}/R_{t+1}}{w_{1,t}}\right]}{(1-\tau_t^w)(1+\beta+\varphi)}, \quad (6)$$

[5] We do not specify the pollution function because the functional form of $d(\cdot)$ has no effect on theoretical results.

and labor supplied by the old:

$$\lambda_{2,t+1} = \frac{(1+\beta) - \gamma\beta \left[\tau^w_{t+1} \dfrac{\lambda_{1,t+1} w_{1,t+1}}{w_{2,t+1}} + (1-\tau^w_t) \dfrac{\lambda_{1,t} w_{1,t}}{w_{2,t+1}/R_{t+1}} \right]}{(1+\gamma)(1+\beta) - \gamma} \tag{7}$$

The time spent working (λ_2) rather than retiring is determined by the presence of a PAYG in the first place. Indeed, the term in brackets simply reflects the social security wealth (difference between retirement benefits and contributions). Second, the decision to retire depends on relative wages across ages and periods in life. Third, if investment by the young is large, the old spend more time working. This is due to the fact that they are healthier and receive less retirement benefits in that case.

Finally, optimal individual health expenditure is given by:

$$\frac{H(m_t) + (1 - d(P_t))h_{1,t}}{H'(m_t)} - \frac{\beta(1-\phi)}{\phi\varphi}(1 - m_t - \lambda_{1,t}) = 0 \tag{8}$$

Heath expenditure m_t is positively related to the level of pollution P_t, negatively related to labor supply $\lambda_{1,t}$ and the health status $h_{1,t}$ of the young.

2.2 Firms

Identical firms operate under perfect competition. They produce a final good Y_t using the production function:

$$Y_t = BK_t^{\alpha_K} L_t^{\alpha_L} E_t^{1-\alpha_K-\alpha_L}$$

where K_t is the amount of physical capital, L_t is aggregate efficient labor, E_t is the flow of pollution emissions and $\alpha_K, \alpha_L \in (0,1)$.[6]

We assume that efficient units of labor supplied by the young depend on their respective productivity, which is influenced by their health status (denoted by $h_{1,t}$ for

[6]The introduction of polluting emissions as a factor of production is justified by Stokey (1998) as follows. Let us consider that actual output is defined as $Y = zy_p$ where $z \in [0,1]$ is the index of emission rate and $y_p = K^{\alpha_p} L^{1-\alpha_p}$ ($\alpha_p \in]0,1[$) is potential output. The flow of pollution is defined as $E = y_p z^{\beta_p}$ ($\beta_p > 1$): the more the production technology is polluting (high z) (or the higher is potential output), the greater emissions are. Rewriting $z = E^{1/\beta_p} y_p^{-1/\beta_p}$, we obtain $Y = E^{1/\beta_p} \left[K^{\alpha_p} L^{1-\alpha_p}\right]^{-1/\beta_p} = K^{\alpha_K} L^{\alpha_L} E^{1-\alpha_K-\alpha_L}$ with $\alpha_K \equiv \alpha_p(1-1/\beta_p)$. See also Xepapadeas (2005, p.1224) for other justifications.

young and $h_{2,t}$ for old born at $t-1$). In contrast with previous contributions, we assume that efficient units of labor provided by the old and the young may be not perfectly substitutes in production. Therefore, aggregate efficient labor is defined as:

$$L_t = \left[\psi \left(h_{1,t}\ l_{1,t}\right)^{\theta} + (1-\psi)\left(h_{2,t}\ l_{2,t}\right)^{\theta}\right]^{1/\theta} \qquad \theta \leq 1,\ \psi \in (0,1)$$

where $l_{1,t}$ (respectively $l_{2,t}$) is the amount of labor supplied by the young (the old) at time t, and $h_{1,t}l_{1,t}$ (resp. $h_{2,t}l_{2,t}$) is efficient labor supplied by the young (the old).[7] The parameter θ measures the degree of substitutability between old and young workers in production. The elasticity of substitution between the two types of labor equals $1/(1-\theta)$. When $\theta = 1$, young and old workers are perfect substitutes. When $0 \leq \theta < 1$, they are imperfect substitutes. When $\theta = 0$, they are unitary substitutes. When $\theta < 0$, they are complements.

The profit of the firm in period t is $Y_t - w_{1,t}l_{1,t} - w_{2,t}l_{2,t} - R_tK_t - \tau E_t$, where R_t is the rental rate of capital and τ is an environmental tax levied by the government. Profit-maximization yields the following first-order conditions:

$$R_t = \alpha_K Y_t / K_t \tag{9}$$

$$w_{1,t} = \alpha_L Y_t / L_t \frac{\partial L_t}{\partial l_{1,t}} \qquad \text{and} \qquad w_{21,t} = \alpha_L Y_t / L_t \frac{\partial L_t}{\partial l_{2,t}} \tag{10}$$

$$\tau = (1 - \alpha_K - \alpha_L) Y_t / E_t \tag{11}$$

Equation (11) shows that firms pollution emissions increase with output and decrease with environmental taxation. This equation enables us to express final output in terms of physical capital, labor and the environmental tax:

$$Y_t = f(\tau) K_t^{\alpha} L_t^{1-\alpha} \tag{12}$$

[7]We assume that individual productivity is only captured by health-status. Even if we are aware that there are other factors affecting productivity when people get older (like human capital accumulation through experience, for example), we follow (Garibaldi 2010, p.1) and consider that human capital is really effective only when it is embodied in healthy people.

with $L_t = \left[\psi\left(h_{1,t}l_{1,t}\right)^{\theta} + (1-\psi)\left(h_{2,t}l_{2,t}\right)^{\theta}\right]^{1/\theta}$, $f(\tau) \equiv B^{1/(\alpha_K+\alpha_L)}\left(\frac{1-\alpha_K-\alpha_L}{\tau}\right)^{\frac{1-\alpha_K-\alpha_L}{\alpha_K+\alpha_L}}$ and $\alpha \equiv \alpha_K/(\alpha_K+\alpha_L)$.

2.3 Government and pollution

The government budget is balanced at all times and tax revenues match government expenditure of the same nature. The Pay-as-you-go retirement system is solely financed by revenue from the payroll tax. Furthermore, public abatement activities, denoted A_t, are solely financed by the revenue from the environmental tax on the flow of pollution emissions, such that:

$$A_t = \tau E_t$$

The pollution stock rises with the flow of pollution emissions and is reduced by abatement activities:

$$P_{t+1} = (1-\sigma)P_t + E_t - A_t$$

where $\sigma > 0$ is the nature regeneration rate, and $E_t - A_t$ is the net flow of pollution at date t. From the expressions of E_t and A_t, it follows:

$$P_{t+1} = (1-\sigma)P_t + (1-\alpha_K-\alpha_L)\left(\frac{1}{\tau}-1\right) f(\tau) K_t^{\alpha} L_t^{1-\alpha} \tag{13}$$

2.4 Equilibrium

First, we consider the equilibrium in labor markets. Young agents supply $\lambda_{1,t}N$ units of labor and firms demand $l_{1,t}$: in equilibrium $l_{1,t} = \lambda_{1,t}N$. Old agents supply $\lambda_{2,t}N$ units of labor and firms demand $l_{2,t}$: in equilibrium $l_{2,t} = \lambda_{2,t}N$. The aggregate labor supply is given by:

$$L_t = N\left[\psi\left(\lambda_{1,t}h_{1,t}\right)^{\theta} + (1-\psi)\left(\lambda_{2,t}h_{2,t}\right)^{\theta}\right]^{1/\theta} \tag{14}$$

From equation (10), we obtain:

$$w_{1,t} = \psi \alpha_L f(\tau) \tilde{k}_t^{\alpha} h_{1,t} \left[\psi + (1-\psi) \left(\frac{\lambda_{2,t} h_{2,t}}{\lambda_{1,t} h_{1,t}} \right)^{\theta} \right]^{(1-\theta)/\theta} \tag{15}$$

where $\tilde{k}$ is the capital stock per efficient worker, and:

$$w_{2,t} = (1-\psi) \alpha_L f(\tau) \tilde{k}_t^{\alpha} h_{1,t} \left(\frac{h_{2,t}}{h_{1,t}} \right)^{\theta} \left(\frac{\lambda_{1,t}}{\lambda_{2,t}} \right)^{1-\theta} \left[\psi + (1-\psi) \left(\frac{\lambda_{2,t} h_{2,t}}{\lambda_{1,t} h_{1,t}} \right)^{\theta} \right]^{(1-\theta)/\theta} \tag{16}$$

Therefore, the relative reward of young labor with respect to old labor is:

$$\frac{w_{1,t}}{w_{2,t}} = \frac{\psi}{1-\psi} \left(\frac{h_{1,t}}{h_{2,t}} \right)^{\theta} \left(\frac{\lambda_{2,t}}{\lambda_{1,t}} \right)^{1-\theta} \tag{17}$$

Finally, equations (9) and (12) give us the expression of the interest rate:

$$R_t = \alpha_K f(\tau) \tilde{k}_t^{\alpha-1} \tag{18}$$

Clearing of goods and capital markets leads to the equilibrium condition $K_{t+1} = s_t N_t$ which is expressed in terms of per worker capital stock:

$$\tilde{k}_{t+1} \equiv \frac{K_{t+1}}{L_{t+1}} = \left[\psi \left(\lambda_{1,t+1} h_{1,t+1} \right)^{\theta} + (1-\psi) \left(\lambda_{2,t+1} h_{2,t+1} \right)^{\theta} \right]^{-1/\theta} s_t \tag{19}$$

Using (12) and (14), output per capita is defined as:

$$y_t = f(\tau) \tilde{k}_t^{\alpha} \frac{L_t}{2N} \tag{20}$$

Therefore, the economy can be summarized by equations (3), (5) to (8), (13) to (16), (18) to (20).

3 Steady-state equilibrium

In this section, we investigate the influence of the environmental tax on the steady-state equilibrium.

The steady-state equilibrium is such that $\left\{ m_t, R_t, h_{2,t}, s_t, \tilde{k}_t, w_{1,t}, w_{2,t}, P_t, \lambda_{1,t}, \lambda_{2,t} \right\} = \left\{ m^\star, R^\star, h_2^\star, s^\star, \tilde{k}^\star, w_1^\star, w_2^\star, P^\star, \lambda_1^\star, \lambda_2^\star \right\}$, where variables with a * are constant, with $\tau^w = \tau^w_{t+1} = \tau^w$. Thus, the steady-state equilibrium is defined by the following equations:

$$\tilde{k}^\star = \left[\psi \lambda_1^{\star\theta} + (1-\psi) \left(\lambda_2^\star \Delta_h^\star \right)^{\theta} \right]^{-1/\theta} s^\star / \bar{h} \tag{E1*}$$

$$s^\star = \frac{\beta(1-\tau^w)\lambda_1^\star w_1^\star - \lambda_2^\star w_2^\star / R^\star - \tau^w \lambda_1^\star w_1^\star / R^\star}{1+\beta} \tag{E2*}$$

$$\lambda_2^\star = \frac{(1+\beta) - \gamma\beta \dfrac{\lambda_1^\star w_1^\star}{w_2^\star / R^\star}\left[1-\tau^w + \tau^w / R^\star\right]}{(1+\gamma)(1+\beta)-\gamma} \tag{E3*}$$

$$\lambda_1^\star = \frac{(1+\beta)(1-m^\star) - \varphi \dfrac{\lambda_2^\star w_2^\star / R^\star}{(1-\tau^w) w_1^\star}}{1+\beta+\varphi\left[1+\frac{\tau^w}{(1-\tau^w)R^\star}\right]} \tag{E4*}$$

$$\frac{h_2^\star}{H'(m^\star)} - \frac{\beta(1-\phi)}{\phi\varphi}(1-m^\star-\lambda_1^\star) = 0 \tag{E5*}$$

$$h_2^\star = H(m^\star) + \left[1-d(P^\star)\right]\bar{h} \tag{E6*}$$

$$w_1^\star = \psi\alpha_L f(\tau)\tilde{k}^{\star\alpha}\bar{h}\left[\psi + (1-\psi)\left(\frac{\lambda_2^\star}{\lambda_1^\star}\Delta_h^\star\right)^\theta\right]^{(1-\theta)/\theta} \tag{E7*}$$

$$w_2^\star = (1-\psi)\alpha_L f(\tau)\tilde{k}^{\star\alpha} h_2^\star \left(\frac{\lambda_1^\star}{\lambda_2^\star \Delta_h^\star}\right)^{1-\theta}\left[\psi + (1-\psi)\left(\frac{\lambda_2^\star \Delta_h^\star}{\lambda_1^\star}\right)^\theta\right]^{(1-\theta)/\theta} \tag{E8*}$$

$$R^\star = \alpha_K f(\tau)\tilde{k}^{\star\alpha-1} \tag{E9*}$$

$$P^\star = \sigma^{-1}(1-\alpha_K-\alpha_L)\left(\frac{1}{\tau}-1\right) f(\tau)\tilde{k}^{\star\alpha}L^\star \tag{E10*}$$

$$L^\star = N\lambda_1^\star \bar{h}\left[\psi + (1-\psi)\left(\frac{\lambda_2^\star \Delta_h^\star}{\bar{\lambda}_1}\right)^\theta\right]^{1/\theta} \tag{E11*}$$

From (E6*), (E10*) and the definition of $\Delta_h^\star$, we obtain:

$$\Delta_h^\star = H(m^\star)\bar{h}^{-1} + 1 - d\left(\sigma^{-1}(1-\alpha_K-\alpha_L)\left(\frac{1}{\tau}-1\right) f(\tau)\tilde{k}^{\star\alpha}L^\star\right) \tag{E5*-1}$$

Using equations (E1*), (E2*), (E7*) to (E9*), we obtain:

$$\left[\frac{\lambda_2^\star}{\lambda_1^\star}\Delta_h^\star\right]^\theta = \mathcal{D}(R^\star) \equiv \left(\frac{\psi}{1-\psi}\right)\frac{\left[\beta(1-\tau^w)R^\star - \tau^w - \frac{\alpha_K}{\alpha_L}(1+\beta)\right]}{1+\frac{\alpha_K}{\alpha_L}(1+\beta)} > 0 \tag{21}$$

with $\mathcal{D}'(R^\star) > 0$.[8]

[8]Under a realistic choice of parameters, the term into brackets in the right-hand side of equation (21) is positive.

Lemma 1. *When $\theta = 0$, there exists a unique interest rate $R^\star$, which is independent from τ.*

Proof. Straightforward from (21) and (E5*-1). □

This Lemma identifies one special case in which environmental taxation does not affect the health profile and equilibrium interest rate: When the elasticity of substitution between young and old labor is one ($\theta = 0$), the health profile has no effect on the wage profile. As shown by equation (17), the wage profile solely depends upon the labor supply profile. In that case, a change in the health profile does not trigger any of the new effects. In what follows, we will distinguish between the cases when $\theta = 0$, and $\theta \neq 0$.

Using (E11*), aggregate labor in efficiency units can be expressed as:

$$L^\star = N_t \lambda_1^\star \bar{h} \psi^{1/\theta} \left[\frac{1 - \tau^w + \beta(1-\tau^w)R^\star}{(1+\beta)\frac{\alpha_K}{\alpha_L} + 1} \right]^{1/\theta} \tag{22}$$

Using (E3*), (E8*), (E9*) and (21), we obtain:

$$\lambda_1^\star = \Lambda_1(R^\star, m^\star) \equiv \frac{(1-\tau^w)(1+\beta)(1-m^\star)}{(1-\tau^w)(1+\beta+\varphi) + \varphi \left[\tau^w + \left(\frac{1-\psi}{\psi}\right) \mathcal{D}(R^\star) \right] / R^\star} < 1 - m^\star \tag{23}$$

with $\partial \Lambda_1(\cdot)/\partial R^\star < 0$ and $\partial \Lambda_1(\cdot)/\partial m^\star < 0$.[9]

Using (E5*), (E8*), (E9*) and (21), we obtain:

$$\lambda_2^\star = \Lambda_2(R^\star) \equiv \frac{(1+\beta)}{(1+\gamma)(1+\beta) - \gamma + \gamma\beta \left[1 - \tau^w + \tau^w/R^\star\right] \left(\frac{\psi}{1-\psi}\right) R^\star/\mathcal{D}(R^\star)} \tag{24}$$

with $\partial \Lambda_2(\cdot)/\partial R^\star > 0$.[10]

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[9] Note that at the denominator of (23), $\left[\tau^w + \left(\frac{1-\psi}{\psi}\right) \mathcal{D}(R^\star) \right] / R^\star = \frac{\beta(1-\tau^w) - (1-\tau^w)(1+\beta)\frac{\alpha_K}{\alpha_L}/R^\star}{(1+\beta)\alpha_K/\alpha_L + 1}$ is an increasing function of $R^\star$.

[10] Note that, at the denominator of (24), $R^\star/\mathcal{D}(R^\star)$ is a decreasing function of $R^\star$.

Using previous results, we can express the stock of pollution in the long run:

$$P^\star = \Pi(R^\star, m^\star; \tau) \equiv \frac{(1-\alpha_K-\alpha_L)\alpha_K^{\frac{\alpha}{1-\alpha}} N\bar{h}\psi^{1/\theta}}{\sigma} \left[(1+\beta)\frac{\alpha_K}{\alpha_L}+1\right]^{-1/\theta}$$
$$\times \left(\frac{(1-\tau)\, f(\tau)^{\frac{1}{1-\alpha}}}{\tau}\right) R^{\star\frac{-\alpha}{1-\alpha}} \left[1-\tau^w+\beta(1-\tau^w)R^\star\right]^{1/\theta} \Lambda_1(R^\star, m^\star) \quad (25)$$

with $\Pi_1(R^\star, m^\star; \tau) < 0$ for $\theta < 0$ (respectively $\Pi_1(R^\star, m^\star; \tau) > 0$ for $\theta > 0$[11]), $\Pi_2(R^\star, m^\star; \tau) < 0$ and $\Pi_3(R^\star, m^\star; \tau) < 0$.

In the steady-state equilibrium, using (21), the allocation of time for health investment $m^\star$ is defined by equation (E5*):

$$\frac{\mathcal{D}(R^\star)^{1/\theta}}{\Lambda_2(R^\star)} = \frac{\beta(1-\phi)H'(m^\star)}{\phi\varphi\bar{h}} \left[\frac{(1-\tau^w)\varphi + \varphi\left[\tau^w + \left(\frac{1-\psi}{\psi}\right)\mathcal{D}(R^\star)\right]/R^\star}{(1-\tau^w)(1+\beta)}\right] \quad (26)$$

The following relation defines $m^\star$ as a function of $R^\star$:

$$m^\star = \Omega(R^\star), \quad (27)$$

with $\partial\Omega(R^\star)/\partial R^\star > 0$ when $\theta < 0$ (resp. $\partial\Omega(R^\star)/\partial R^\star < 0$ when $\theta > 0$).[12]

Equation (26) gives the expression of $\Delta_h^\star$ with respect to $R^\star$ and τ:

$$\Delta_h^\star = \mathcal{H}(R^\star; \tau) \equiv H\left(\Omega(R^\star)\right)/\bar{h} + \left[1 - d\left(\Pi(R^\star, \Omega(R^\star); \tau)\right)\right] \quad (28)$$

with $\mathcal{H}_1(R^\star; \tau) > 0$ when $\theta < 0$ (resp. $\mathcal{H}_1(R^\star; \tau) < 0$ when $\theta > 0$) and $\mathcal{H}_2(R^\star; \tau) > 0$ $\forall\theta \leq 1$.

---

[11]Under the sufficient condition $\alpha \leq 1/2$, which is a realistic value for this parameter.

[12]The RHS is a decreasing function of $m^\star$ and is increasing in $R^\star$. When $\theta < 0$, the LHS is decreasing in $R^\star$ and therefore, $m^\star$ is unique and it increases in $R^\star$. Equation (26) may be written as:

$$\mathcal{D}(R^\star)^{1/\theta-1} = \frac{\beta(1-\phi)H'(m^\star)}{(1-\tau^w)\phi\varphi\bar{h}} \frac{\left[(1-\tau^w)\varphi + \varphi\left[\tau^w + \left(\frac{1-\psi}{\psi}\right)\mathcal{D}(R^\star)\right]/R^\star\right]}{\left[(1+\gamma)(1+\beta)-\gamma\right]\mathcal{D}(R^\star) + \gamma\beta\left[1-\tau^w+\tau^w/R^\star\right]\left(\frac{\psi}{1-\psi}\right)R^\star}.$$

The RHS is decreasing in $R^\star$ and the LHS is increasing in $R^\star$ when $0 < \theta \leq 1$. In this case, $m^\star$ is unique and decreasing in $R^\star$.

Using equation (21) and previous results we can express the steady-state interest rate with respect to τ:

$$\left\{\frac{\Lambda_2(R^\star)}{\Lambda_1(R^\star,\Omega(R^\star))}\mathcal{H}(R^\star;\tau)\right\}^\theta = \mathcal{D}(R^\star) \tag{29}$$

As a result, we obtain the following proposition:

Proposition 1. *In the stationary equilibrium, there is a unique and positive interest rate such that:*

$$R^\star = \mathcal{R}(\tau)$$

with:

(i) $\mathcal{R}'(\tau) < 0$ *when old workers and young workers are complement in production* $(\theta < 0)$*.*

(ii) $\mathcal{R}'(\tau) = 0$ *when old workers and young workers are unitary substitutes in production* $(\theta = 0$*, Cobb-Douglas case).*

(iii) $\mathcal{R}'(\tau) > 0$ *when old workers and young workers are non-unitary substitutes in production* $(0 < \theta \leq 1)$*.*

Proof. See Appendix A. □

Corollary 1.

(i) $m^\star = \mathcal{M}(\tau)$ *with* $\mathcal{M}'(\tau) < 0, \forall\theta \leq 1$;

(ii) $\lambda_1^\star = \mathcal{L}_1(\tau)$ *with* $\mathcal{L}_1'(\tau) > 0$ *for* $\theta \leq 0$;

(iii) $\lambda_2^\star = \mathcal{L}_2(\tau)$ *with* $\mathcal{L}_2'(\tau) \gtreqless 0$ *for* $\theta \gtreqless 0$

(iv) $h_2^\star = \mathcal{H}(\tau)$ *with* $\mathcal{H}'(\tau) > 0, \forall\theta \leq 1$;

(v) $P^\star = \mathcal{P}(\tau)$ *with* $\mathcal{P}'(\tau) < 0, \forall\theta \leq 1$;

Proof. See Appendix B. □

Proposition 1 states that when health changes over the life-cycle, environmental taxation impacts the interest rate. Therefore, it influences saving. This general equilibrium mechanism is at the heart of the new effect of environmental taxation which we will identify as the *health-saving effect*.

The health profile influences the efficient wage profile (equation 17). When the environmental tax increases, other things equal, health deteriorates less over the life-cycle. If young and old labor are substitutes (complements) the efficient wage profile improves (deteriorates), resulting in less (more) saving. The health saving effect is negative (positive), which is reflected by the opposite change in interest rate. Therefore, the change in the health profile alone triggers the health saving effect.[13] The health profile is also influenced by investment in health, which can decrease as a result of a less polluted environment (Corollary 1i). If investment in health is endogenous, it is therefore likely to limit (or even reverse) the effect of environmental taxation on the efficient wage profile, and the health-saving effect. Because investment in health requires time, it influences the labor choice by the young causing the "young labor effect" (Corollary 1ii). It also influences retirement decision by the old causing the "retirement effect" (Corollary 1iii). The environmental tax generates positive or negative retirement effect depending whether young and old labor are unitary substitutes or complements.

The expression giving per capita output enables us to identify the previously described transmission mechanisms of a tighter environmental tax.

$$y^\star = \left(\frac{1}{2}\right) \underbrace{f(\tau)^{1/(1-\alpha)}}_{I} \underbrace{\left(\frac{\alpha_K}{\mathcal{R}(\tau)}\right)^{\alpha/(1-\alpha)}}_{II} \left[\psi[\bar{h}\underbrace{\mathcal{L}_1(\tau)}_{IIIb}]^\theta + (1-\psi)[\underbrace{\mathcal{H}(\tau)}_{IIIa}\underbrace{\mathcal{L}_2(\tau)}_{IIIc}]^\theta\right]^{1/\theta} \tag{30a}$$

when $\theta \neq 0$, and:

$$y^\star = \left(\frac{1}{2}\right) \underbrace{f(\tau)^{1/(1-\alpha)}}_{I} \left(\frac{\alpha_K}{R^\star}\right)^{\alpha/(1-\alpha)} [\bar{h}\underbrace{\mathcal{L}_1(\tau)}_{IIIb}]^\psi [\lambda_2^\star \underbrace{\mathcal{H}(\tau)}_{IIIa}]^{1-\psi} \tag{30b}$$

when $\theta = 0$.

[13]We show proof of this in Appendix C.

Proposition 2. *The effect of the environmental tax on steady-state output per capita is the sum of standard crowding-out and productivity effects as well as new life cycle effects.*

Proof. From equations (30a) and (30b) □

In the general case, we retrieve the standard transmission mechanisms of environmental taxation (*I* and *IIIa*) respectively producing the crowding-out and productivity effects. We also retrieve mechanism *II* producing the health-saving effect, in the presence of endogenous investment in health. With endogenous labor supply and retirement choices, we identify two new channels through which environmental taxation affects per capita output: Channel *IIIb* produces the young labor effect and channel *IIIc* the retirement effect.

The table below provides a qualitative summary of the effects of environmental taxation on steady state output per capita.

	$\theta > 0$	$\theta < 0$	$\theta = 0$
I ⇾ crowding-out effect	−	−	−
II ⇾ health-saving effect	−	+	0
$IIIa$ ⇾ young labor effect	?	+	+
$IIIb$ ⇾ productivity effect	+	+	+
$IIIc$ ⇾ retirement effect	+	−	0

Table 1: Effects on output per capita and substitutability of young and old labor

Proposition 3. *Depending on the degree of substitutability between young and old workers, the sum of new life-cycle effects reinforces or attenuates the effect of the environmental tax.*

Proof. From Table 1. □

4 Numerical examples

We simulate the model. The main objective of this section is to get a sense of the magnitude of the new effects of environmental taxation on output and welfare. We also provide a decomposition of the effect on output into crowding-out, health-saving, productivity, young labor and retirement effects, such that:

$$\frac{\partial y^\star}{\partial \tau} = \underbrace{\frac{\partial y^\star}{\partial f(\tau)} f'(\tau)}_{\textit{crowding-out}} + \underbrace{\frac{\partial y^\star}{\partial \mathcal{R}(\tau)} \mathcal{R}'(\tau)}_{\textit{health saving}} + \underbrace{\frac{\partial y^\star}{\partial \mathcal{L}_1(\tau)} \mathcal{L}_1'(\tau)}_{\textit{young labor}} + \underbrace{\frac{\partial y^\star}{\partial \mathcal{H}(\tau)} \mathcal{H}'(\tau)}_{\textit{productivity}} + \underbrace{\frac{\partial y^\star}{\partial \mathcal{L}_2(\tau)} \mathcal{L}_2'(\tau)}_{\textit{retirement}} \quad (30)$$

We compare our results with those of the existing literature, which assumes a flat health profile and perfect substitutability of young and old labor.

The numerical results are to be taken with caution considering the following facts. The model is very stylized, which is necessary to derive theoretical results and identify new life-cycle effects of environmental taxation. As a consequence, our numerical exercise focuses on assessing the magnitude of those new effects rather than providing a perfect assessment of the overall effects of environmental taxes on output or welfare. The stylized theoretical model is also limited in its ability to reproduce all the characteristics of the US economy. The values of some of parameters of the model are uncertain in the current state of empirical knowledge. Therefore, we consider that a reasonable strategy is to adjust the parameter values to reproduce some of the most salient features of the US economy. Specifically, we adjust the model unobservable parameters to reproduce the benchmark economy while we consider different plausible degrees of substitutability between young and old workers. We study the robustness of our results providing alternative calibrations that also reproduce the characteristics of the benchmark economy each time.

4.1 Calibration

We first calibrate the model assuming that the duration of each period is 30 years, which is usual in the literature. The first period covers ages 20-50 and the second period covers ages 50-80. Based on De La Croix and Michel (2002), we choose the rate of time preference β equal to 0.3 (equivalent to a quarterly psychological discount factor equal to 0.99, which is standard in the Real Business Cycle (RBC) literature). Similarly, in the RBC literature, capital's share in income α is around 1/3. Because $\alpha = \alpha_K/(\alpha_K + \alpha_L)$, we set $\alpha_K = 0.3$ and $\alpha_L = 0.6$. The weight of consumption in utility is in line with the range of values considered by French (2005). The weight of consumption in utility ϕ is in line with the range of values considered by French (2005). The social security tax in the US is 12.4% (Gruber 2013). OECD statistics tables on environmental policy instruments indicate that environmental taxation represents 0.47% of GDP in 2012 in the US. Furthermore, the average environmental tax in OECD represents 1.09% of GDP in 2012, and the highest environmental tax rate is 2.20% of GDP in Denmark. Thus, we will use 0.5% of GDP for our benchmark environmental tax. We will simulate the effects of an increase in environmental taxation from 0.5% to 1% (OECD average) and from 1% to 2%.

Murphy and Welch (1992, Table XI page 322) estimate elasticities of complementarity between individuals with up to 20 years of experience and individuals with more than 20 years of experience, including high school and college graduates. The authors find that young and old workers with similar or different skill levels are generally complements. The range of elasticities obtained, depending on the model and the cohort observed yields a value of θ between -0.7 and 0.6. Hebbink (1993, page 220) estimates elasticities of substitution between young, middle-age, and old workers. He finds that workers of different age groups are complements, which yields a value of θ between -0.39 and -0.72. Based on Card and Lemieux' (2001) estimates, the elasticity of substitution across age groups for both high school and college educated workers yields a value of θ equal to 0.8 (page 27). Ottaviano and Peri (2012) estimate that workers within the same education group but different levels of experience have even larger elasticities of substitution than Card and Lemieux (2001) and their estimates yield values of θ beyond the range of possible values in our model. Thus, for our benchmark case, we use the recent estimate for the US by Card and Lemieux (2001). We adjust the value of parameter ψ to match the ratio λ_1/λ_2 of the US economy. Based on the time spent on "working and work related activities" per age in US the time expenditure survey 2014, this ratio equals 5.

There is great uncertainty regarding the values of the parameters of the investment in health and pollution functions . For the numerical simulations, the investment in health function is defined as $H(m) = \eta m^{\epsilon}$, with $\eta > 0$ and $\epsilon \in]0, 1[$. We also define the pollution function as $d(P^{\star}) = \xi (P^{\star})^{\varsigma}$ with $\xi > 0$ and $\varsigma > 0$. [14] The health profile depends on investment in health and pollution functions. Our choice of parameters yields a decreasing initial health profile. Our initial health profile reproduces the steepness of the heath profile based on Self-Rated Health, which is a widely used indicator of health. Specifically, we use Latham and Peek (2013) study who provide the percentage of individuals reporting good or excellent health between 18 and 44 years old and between 45 and 75 years old to obtain a proxy for the decline in health equal to $h_2/h_1 = 0.7$. The economics literature does not provide guidance regarding the choice of the parameters of health and pollution functions. The best we can do is therefore to provide a sensitivity analysis of our numerical results to calibration of the investment in health and pollution functions (Table 13).

The unobservable parameters φ, γ, η, ψ and ξ are adjusted such that total leisure time is close to two third of individual time (Prescott 2004), the time spent on investment in health is within the range of 3.9 to 7.1 percent (which represents time of lost leisure solely due to bad health (French 2005)), and the interest rate on annual basis is around 5%, that is $R = (1, 05)^{30} \approx 4$. Welfare is simply measured by utility and B is chosen to obtain the 2014 US GDP per capita.

Our choice of parameters is summarized in Table 2. Table 3 shows that our model reproduces the main features of the US economy with the exception of the saving rate ,

[14] We checked that in our simulations the computed function $d(\cdot)$ is always lower than unity.

which is high. Table 3 also indicates the effect of an increase in the environmental tax from 0.5% (the current US rate) to 1% (OECD average) and to 2% (close to highest rate in OECD).

Table 2: Calibration

Parameter	Value
Preferences and health	
φ	3.216
ϕ	0.6
β	0.3
γ	1.5565
h_1	1
η	9.504
ϵ	0.5
Production and labor substitutability	
α_K	0.3
α_L	0.6
B	86
θ	0.8
ψ	0.553
Government and pollution	
τ	0.05
τ_w	0.124
ξ	0.354
σ	0.9
ς	0.25

Table 3: The economy and the environmental tax

τ	**0.5%**	1%	2%
$\Delta_h^\star$	**0.7**	0.840	0.982
Leisure*	**0.67**	0.687	0.698
$R^\star$	**4**	4.327	4.667
$\lambda_1^\star$	**0.25**	0.255	0.257
$\lambda_2^\star$	**0.05**	0.060	0.068
m^*	**0.08**	0.058	0.044
s^*	**0.15**	0.139	0.129
y^*	**54.663**	50.352	46.087

4.2 Results

Table 4: Effects of environmental taxation (%)

	τ	**0.5**% → 1%	1% → 2%
	Welfare	-0.543	-1.728
	Crowding-out	-11.12	-11.12
+	Health-saving	-4.086	-3.920
+	Productivity	2.867	3.051
+	Young labor	1.568	2.390
+	Retirement	2.731	2.477
=	*Output per capita*	*-8.039*	*-7.119*

Proposition 4. *The simulated model calibrated on the US economy indicates that overall, the new life-cycle effects alleviate the negative effects of environmental taxation on output and may reverse positive welfare effects.*

Proof. From Table 4. □

Our numerical results are consistent with the theoretical results of Table 1. Furthermore, with our choice of parameters, the negative effects of environmental taxation dominate the positive effects, resulting in a decrease in output. The crowding out effect and the health-saving effect decrease output per capita. The health saving, young labor and retirement effects are quantitatively significant. In our base case, young and old labor are imperfect substituts. The environment tax limits wage deterioration over the life-cycle, resulting in a negative health-saving effect. The decrease in time invested in health yields an increase in labor supply in the first stage of life, resulting in a positive young labor effect and a decrease in labor supply in the second stage of life resulting in a postive retirement effect.

When the environmental tax is increased, the effect on welfare is negative. The positive marginal effect of health is smaller than the negative effect of young labor increase on welfare.

Table 5: Effects of environmental tax with flat health profile (%)

	τ	$\mathbf{0.5}\% \rightarrow 1\%$	$1\% \rightarrow 2\%$
	Welfare	9.589	8.061
	Crowding-out	-11.12	-11.12
+	Health-saving	0.508	0.379
+	Productivity	2.618	2.530
+	Young labor	1.942	1.471
+	Retirement	-0.378	-0.284
=	*Output per capita*	*-6.430*	*-7.023*

Proposition 5. *The simulated model calibrated on the US economy indicates that ignoring the life-cycle characteristics of the health profile may result in understating the negative effects of environmental taxation on output and overstating welfare effects.*

Proof. From Table 5. □

In Table 5, we simulate the effect on macroeconomic variables in the case when the health profile is flat (keeping investment in health m endogenous).[15] When the health profile is flat, recall that the health status improves with the environmental tax *over the entire life-cycle*, shifting the health profile. As a result of the health profile shifting-up, productivity, income and saving increase. The decrease in time invested in health yields a positive young labor effect. People retire earlier as the result of high productivity at old age. Our numerical simulations indicate that, when the initial tax doubles , if the

[15] We recalibrate the model with flat health profile to replicate US data. Parameters are similar to those in Table 2 except, $\eta = 9.504$, $\varphi = 0.622$, $\xi = 0.058$ and $B = 97$.

change in health profile between the two periods in life is ignored, the decrease in output per capita is understated by about 1.5 percentage points compared to the base case.

Additionally, the positive effect on welfare is overstated by about ten percentage points compared to the base case when the change in the health profile is ignored. When the tax is increased further, the difference between the base case (with a life cycle health profile) and the case with a flat health profile becomes smaller as all marginal effects become smaller.

Comparing Table 4 and Table 5, we find that the decrease in output per capita is not the result of an overwhelmingly important crowding-out effect but the cumulated result of several general equilibrium effects related to life-cycle choices.

Table 6: Double environmental taxation and labor substitutability

	τ: 0.5%→ 1% θ	-1	**0.8**	1
	Welfare	0.691	-0.543	-1.490
	Crowding-out	-11.12	-11.12	-11.12
+	Health-saving	1.141	-4.086	-7.510
+	Productivity	2.782	2.867	2.920
+	Young labor	2.115	1.568	1.269
+	Retirement	-0.864	2.731	4.662
=	*Output per capita*	-5.945	-8.039	-9.778

Proposition 6. *By assuming perfect substitution of young and old labor, past contributions are likely to significantly overstate the negative effect of environmental taxation on output.*

Proof. From Table 6. □

In Table 6, we show that when the environmental tax is doubled from 0.5 to 1 percent, our numerical results change depending on the value assigned to the degree of substitutability θ between young and old labor. Consistent with our theoretical section, the numerical results indicate that whether health saving and retirement effects are positive or negative depends on the degree of substitutability between young and old labor. As shown in the table, this significantly affects the analysis regarding the economic effects of the environmental tax. If young and old labor are perfect substitutes, the negative effect of environmental taxation on output per capita is overstated by more than 1.7 percentage points compared to our base case.

4.3 Robustness

In this section, we study the sensitivity of our results to changes in parameters while reproducing the benchmark economy. With our initial calibration, the obtained level of health in the second period of life is 0.7 of the level of health in the first period of life. In Table 9, we simulate the model with different values of $\bar{h}$, to obtain a steeper health profile ($\Delta_h = 0.2$ or $\Delta_h = 0.5$) in the initial equilibrium. We find that in the health profile is initially steeper, the increase in environmental taxation has a positive effect on output and welfare. Indeed, in that case, environmental taxation improves the health profile, enhancing the benefits of environmental taxation more than its negative effects on the economy. As expected, the effect on productivity is increased the most and all other new life-cycle effects are magnified. The crowding-out effect is unchanged since it does not relate to life-cycle elements.

Table 7: Environmental taxation and health profile

	Initial Δh →	0.2	0.5	**0.7**
	Welfare	2.845	-0.125	-0.543
	Crowding-out	-11.12	-11.12	-11.12
+	Health-saving	-8.041	-4.687	-4.086
+	Productivity	5.590	3.283	2.867
+	Young labor	2.449	1.732	1.568
+	Retirement	4.937	3.091	2.731
=	Output per capita	-6.184	-7.700	-8.039

Because of the lack of empirical knowledge about the value of the parameters of health and pollution functions, we simulate the benchmark economy for different values of those parameters. In Table 8 and 9, we show that numerical results are sensitive to the assessment of pollution and health functions. Following an increase in environmental taxation, when ς is small, the positive effects of pollution reduction on health become smaller. Net positive life-cycle effects of environmental taxation decrease and the dominant effect becomes the crowding-out effect, resulting in a drop in output and welfare. When ϵ is small, investment in health has a lower effect on health. As a consequence, in both cases, the effects of pollution reduction on output become much smaller.

Table 8: Environmental taxation and pollution function

	τ: 0.5%→ 1%			
	ς	0.01	**0.25**	0.5
	Welfare	-4.104	-0.543	1.863
	Crowding-out	-11.12	-11.12	-11.12
+	Health-saving	-0.165	-4.086	-7.997
+	Productivity	0.118	2.867	5.560
+	Young labor	0.083	1.568	2.441
+	Retirement	0.121	2.731	4.914
=	*Output per capita*	-10.962	-8.039	-6.200

Table 9: Environmental taxation and health function

	τ: 0.5%→ 1%			
	ϵ	0.1	**0.5**	0.9
	Welfare	5.625	-0.543	-1.700
	Crowding-out	-11.12	-11.12	-11.12
+	Health-saving	-29.539	-4.086	-0.586
+	Productivity	19.862	2.867	0.632
+	Young labor	2.252	1.568	1.532
+	Retirement	12.572	2.731	0.425
=	*Output per capita*	-5.972	-8.039	-9.116

In Table 10, we simulate doubling the environmental tax for different values of the social security tax. In the absence of a social security tax, the retirement system is not a PAYG but a funded system, in which workers save for their own retirement. Our numerical results indicate that the elimination of the PAYG would attenuate the negative impact of environmental taxation on output and would enhance its positive effect on welfare. This result is consistent with the decrease in the overall tax burden resulting from the decrease in the social security tax.

Table 10: Environmental taxation and Social Security tax

	τ: 2%→ 4% τ^w	0%	10%	12.4%
	Welfare	1.04	0.81	0.76
	Crowding-out	-11.12	-11.12	-11.12
+	Health-saving	2.00	1.76	1.71
+	Productivity	7.00	6.72	6.65
+	Young labor	1.65	1.38	1.32
+	Retirement	-1.17	-1.19	-1.18
=	*Output per capita*	-1.65	-2.45	-2.62

5 Conclusion

In this paper, we study the economic effect of environmental taxation when pollution impacts morbidity. In contrast with the existing literature, we propose a model that takes into consideration the interaction between pollution and health over the life-cycle and its consequences on individual optimal choices. We show that, as agents internalize changes in health over the life-cycle, the effect of environmental taxation on output are not limited to the traditional negative crowding-out effect and positive productivity effect. We identify several new general equilibrium effects, the health saving effect, the young labor effect, and the retirement effect. We also show that those new effects can positively or negatively influence output per capita depending on the degree of complementarity or substitutability between young and old labor. We also show that the health saving effect does not appear when models ignore the life-cycle characteristics of the health profile.

Our numerical simulations suggest that those new life-cycle effects attenuate some of the negative effects of environmental taxation on output while they decrease positive welfare effects. The sensitivity of our results to the specifications of pollution, health functions and degree of substitutability of labor across periods of life calls for further empirical investigation to accurately assess the effect of environmental taxes on output and welfare.

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A Proof of Proposition 1

First,

$$\frac{\Lambda_2(R^\star)}{\Lambda_1(R^\star, m^\star)} = \frac{[(1-\tau^w)(1-m^\star)]^{-1}\left\{(1-\tau^w)(1+\beta+\varphi)+\varphi\left[\tau^w+\left(\frac{1-\psi}{\psi}\right)\mathcal{D}(R^\star)\right]/R^\star\right\}}{(1+\gamma)(1+\beta)-\gamma+\gamma\beta\left[1-\tau^w+\tau^w/R^\star\right]\left(\frac{\psi}{1-\psi}\right)R^\star/\mathcal{D}(R^\star)} \tag{A.1}$$

is increasing in $R^\star$ $\forall\theta \leq 1$.

When $\theta = 0$, Lemma 1 applies. When $\theta < 0$, it is straightforward that the LHS of equation (29) is decreasing in $R^\star$ and decreasing in τ. Because the RHS of equation (29) is increasing in $R^\star$, when the steady-state $R^\star$ exists, it is unique and from the theorem of implicit function it is decreasing in τ.

When $\theta \in]0,1]$, equation (29) may be written as:

$$\mathcal{H}(R^\star;\tau) = \mathcal{D}(R^\star)^{1/\theta}\frac{\Lambda_1(R^\star, m^\star)}{\Lambda_2(R^\star)} \tag{A.2}$$

and from equation (E5*), using (21) and (A.1), we have

$$\mathcal{D}(R^\star)^{1/\theta}\frac{\Lambda_1(R^\star, m^\star)}{\Lambda_2(R^\star)} = \frac{\beta(1-\phi)H'(m^\star)(1-m^\star)}{\phi\varphi\bar{h}}\times \left[1-\frac{(1-\tau^w)(1+\beta)}{(1-\tau^w)(1+\beta+\varphi)+\varphi\left[\tau^w+\left(\frac{1-\psi}{\psi}\right)\mathcal{D}(R^\star)\right]/R^\star}\right]$$

which is decreasing in $m^\star$ and increasing in $R^\star$. From equation (27) we know that $m^\star$ is a decreasing function of $R^\star$ when $\theta \in]0,1]$. It comes that the RHS of equation (A.2) is increasing in $R^\star$. Because the LHS of equation (A.2) is decreasing in $R^\star$ and increasing in τ, when the steady-state $R^\star$ exists, it is unique and from the theorem of implicit function it is increasing in τ.

B Proof of Corollary 1

For *(i)* when $\theta \leq 0$, it is straightforward from equation (26) that $H'(m^\star)$ is equal to an expression decreasing function of $R^\star$. Because $H'(m^\star)$ is decreasing in $m^\star$, it means that $m^\star$ is equal to an expression increasing in $R^\star$. Therefore, from Proposition 1, $m^\star$ is decreasing in τ. When $\theta > 0$, from equation (A.2), $H'(m^\star)$ is equal to an expression increasing in $R^\star$. Because $H'(m^\star)$ is decreasing in $m^\star$, it means that $m^\star$ is equal to an expression decreasing in $R^\star$. From Proposition 1, $m^\star$ is therefore decreasing in τ.

For *(ii)*, it is straightforward that $\lambda_1^\star$ is increasing in τ when $\theta < 0$, from equation (23), Corollary 1(i) and Proposition 1. When $\theta = 0$, Lemma 1 applies, therefore from equation (23) and Corollary 1(i) $\lambda_1^\star$ is increasing in τ. When $\theta > 0$, equation (E5*) enables us to write:

$$\lambda_1^\star = [1 - m^\star] - \phi\varphi \frac{H(m^\star) + [1 - d(P^\star)]\,\bar{h}}{\beta(1-\phi)H'(m^\star)}$$

$\lambda_1^\star$ is negatively influenced by $m^\star$ which is decreasing in τ and is positively influenced by $P^\star$ which is decreasing in τ (see below). Without further assumptions about parameters it is not possible to find analytically the influence of τ on $\lambda_1^\star$ when $\theta > 0$.

For *(iii)* see Proposition 1 and equation (22).

For *(iv)*, the RHS of equation (26) is $h_2^\star$. When $\theta \geq 0$, from Proposition 1, Corollary 1(i) and the fact that $\mathcal{D}(R^\star)/R^\star$ is increasing in $R^\star$, the RHS is increasing in τ, therefore $h_2^\star$ is increasing in τ when $\theta \geq 0$. When $\theta < 0$, from equation (29), Proposition (1) and Corollary 1(ii)-(iii), $h_2^\star$ is increasing in τ.

For *(v)*, from equation (E6*), we have $d(P^\star) = H(m^\star) - h_2^\star$. Because $H(\cdot)$ is increasing in $m^\star$, from Corollary 1(i)-(iv) and the fact that $d'(\cdot) > 0$, $P^\star$ is decreasing in τ $\forall\theta \leq 1$.

C Simplified model

To isolate the role of the health profils, we simplify the model by assuming exogenous labor, retirement, and investment in health. In this case, the only decision the young agent makes is about her saving. Thus we set $\varphi = 0$, $\gamma = 0$ and $\tau^w = 0$, and $m = \bar{m}$. First period labor supply becomes $\lambda_1 = 1 - \bar{m} = \bar{\lambda}_1$. From equation (7), second period labor becomes $\lambda_2 = 1$. To easily capture life-cycle health-profile, we assume that the health-status of the young $h_{1,t}$ is exogenous and denoted $\bar{h}$, and in the steady-state, we define $\Delta_h^\star \equiv h_2^\star/\bar{h}$. The steady-state equilibrium is such that $\left\{R_t, h_{2,t}, s_t, \tilde{k}_t, w_{1,t}, w_{2,t}, P_t\right\} = \left\{R^\star, h_2^\star, s^\star, \tilde{k}^\star, w_1^\star, w_2^\star, P^\star\right\}$, where variables with a * are constant. Thus, the steady-state equilibrium is defined by the following equations:

$$\tilde{k}^\star = \left[\psi\bar{\lambda}_1^\theta + (1-\psi)\left(\Delta_h^\star\right)^\theta\right]^{-1/\theta} s^\star/\bar{h} \tag{C.1}$$

$$s^\star = \frac{\beta\bar{\lambda}_1 w_1^\star - w_2^\star/R^\star}{1+\beta} \tag{C.2}$$

$$h_2^\star = H(\bar{m}) + \left[1 - d(P^\star)\right]\bar{h} \tag{C.3}$$

$$w_1^\star = \psi\alpha_L f(\tau)\tilde{k}^{\star\alpha}\bar{h}\left[\psi + (1-\psi)\left(\frac{\Delta_h^\star}{\bar{\lambda}_1}\right)^\theta\right]^{(1-\theta)/\theta} \tag{C.4}$$

$$w_2^\star = (1-\psi)\alpha_L f(\tau)\tilde{k}^{\star\alpha}h_2^\star\left(\frac{\bar{\lambda}_1}{\Delta_h^\star}\right)^{1-\theta}\left[\psi + (1-\psi)\left(\frac{\Delta_h^\star}{\bar{\lambda}_1}\right)^\theta\right]^{(1-\theta)/\theta} \tag{C.5}$$

$$R^\star = \alpha_K f(\tau)\tilde{k}^{\star\alpha-1} \tag{C.6}$$

$$P^\star = \sigma^{-1}(1-\alpha_K-\alpha_L)\left(\frac{1}{\tau}-1\right)f(\tau)\tilde{k}^{\star\alpha}L^\star \tag{C.7}$$

$$L^\star = N\bar{\lambda}_1\bar{h}\left[\psi + (1-\psi)\left(\frac{\Delta_h^\star}{\bar{\lambda}_1}\right)^\theta\right]^{1/\theta} \tag{C.8}$$

From (C.3), (C.7) and the definition of $\Delta_h^\star$, we obtain:

$$\Delta_h^\star = H(\bar{m})\bar{h}^{-1} + 1 - d\left(\sigma^{-1}(1-\alpha_K-\alpha_L)\left(\frac{1}{\tau}-1\right)f(\tau)\tilde{k}^{\star\alpha}L^\star\right) \tag{C.9}$$

Using equations (C.1), (C.2), (C.4) to (C.6), we obtain:

$$\left[\frac{\Delta_h^\star}{\bar{\lambda}_1}\right]^\theta = \tilde{\mathcal{D}}(R^\star) \equiv \left(\frac{\psi}{1-\psi}\right)\frac{\beta R^\star - \frac{\alpha_K}{\alpha_L}(1+\beta)}{1+\frac{\alpha_K}{\alpha_L}(1+\beta)} > 0 \tag{C.10}$$

with $\tilde{\mathcal{D}}'(R^\star) > 0$.

Lemma C.1. *When $\theta = 0$, there exists a unique interest rate $R^\star$, which is independent from τ.*

Proof. When $\theta = 0$, (C.10) becomes $\tilde{\mathcal{D}}(R^\star) = 1$. □

Using (C.8), aggregate efficient labor can be expressed as:

$$L^\star = N\bar{\lambda}_1\bar{h}\psi^{1/\theta}\left[\frac{1+\beta R^\star}{(1+\beta)\frac{\alpha_K}{\alpha_L}+1}\right]^{1/\theta} \tag{C.11}$$

From (C.7), (C.6) and (C.11), the stock of pollution at the steady-state is given by:

$$P^\star = \sigma^{-1}(1-\alpha_K-\alpha_L)\left(\frac{1}{\tau}-1\right)f(\tau)^{\frac{1}{1-\alpha}}\left(\frac{R^\star}{\alpha}\right)^{\frac{-\alpha}{1-\alpha}}N\bar{\lambda}_1\bar{h}\psi^{1/\theta}\left[\frac{1+\beta R^\star}{(1+\beta)\frac{\alpha_K}{\alpha_L}+1}\right]^{1/\theta} \tag{C.12}$$

and using (C.9) and (C.10), we obtain the expression of the steady-state interest rate:

$$d\left(\left(\frac{1-\alpha_K-\alpha_L}{\sigma}\right)\left(\frac{1}{\tau}-1\right)f(\tau)^{\frac{1}{1-\alpha}}\left(\frac{R^\star}{\alpha}\right)^{\frac{-\alpha}{1-\alpha}}N\bar{\lambda}_1\bar{h}\psi^{1/\theta}\left[\frac{1+\beta R^\star}{(1+\beta)\frac{\alpha_K}{\alpha_L}+1}\right]^{1/\theta}\right) + \bar{\lambda}_1\tilde{\mathcal{D}}(R^\star)^{1/\theta} = 1 + \frac{H(\bar{m})}{\bar{h}} \tag{C.13}$$

with $d'(\cdot) > 0$.

Proposition C.1. *In the stationary equilibrium, there is a unique and positive interest rate such that:*

$$R^\star = \mathcal{R}(\tau)$$

with:

(i) $\mathcal{R}'(\tau) < 0$ *when old workers and young workers are complement in production* ($\theta < 0$).

(ii) $\mathcal{R}'(\tau) = 0$ *when old workers and young workers are unitary substitutes in production* ($\theta = 0$, *Cobb-Douglas case).*

(iii) $\mathcal{R}'(\tau) > 0$ *when old workers and young workers are non-unitary substitutes in production* ($0 < \theta \leq 1$).

Proof. (i) When $\theta < 0$, the LHS of equation (C.13) is decreasing in $R^\star$ and decreasing in τ. When the interest rate exists, it is unique and from the theorem of implicit function, $R^\star$ is decreasing in τ. (ii) When $\theta = 0$, $\mathcal{R}'(\tau) = 0$ is straightforward from Lemma C.1. (iii) When $\theta \in]0,1]$, under the sufficient condition $\alpha < 1/2$, which is a realistic value for this parameter, the LHS of (C.13) is increasing in $R^\star$ and decreasing in τ. Therefore, when the interest rate exists, it is unique and from the theorem of implicit function, $R^\star$ is increasing in τ. □

Proposition C.1 states that when health changes over the life-cycle, environmental taxation impacts the interest rate. Therefore, it influences saving. As a result, the change in health profile is at the heart of the health-saving effect.

Corollary C.1.

(i) $P^\star = \mathcal{P}(\tau)$ *with* $\mathcal{P}'(\tau) < 0, \forall \theta \leq 1$;

(ii) $h_2^\star = \mathcal{H}(\tau)$ *with* $\mathcal{H}'(\tau) > 0, \forall \theta \leq 1$;

Proof. From (C.9) and (C.10), $P^\star = 1 + H(\bar{m})/\bar{h} - \bar{\lambda}_1 \tilde{\mathcal{D}}(R^\star)^{1/\theta}$. Therefore, using Proposition C.1, we find the influence of τ on $P^\star$. The impact of τ on $h_2^\star$ is given by (C.3) and Corollary C.1(i). □

The expression giving per capita output enables us to identify the channels of transmission of a tighter environmental tax, *I*, *II* and *III*. Per capita output is given by equations (20) and (C.11), and the results of the previous section:

$$y^\star = \left(\frac{1}{2}\right) \underbrace{f(\tau)^{1/(1-\alpha)}}_{I} \underbrace{\left(\frac{\alpha_K}{\mathcal{R}(\tau)}\right)^{\alpha/(1-\alpha)}}_{II} \left[\psi[\bar{\lambda}_1 \bar{h}]^\theta + (1-\psi)\underbrace{\mathcal{H}(\tau)^\theta}_{III}\right]^{1/\theta}$$

when $\theta \neq 0$, and:

$$y^\star = \left(\frac{1}{2}\right) \underbrace{f(\tau)^{1/(1-\alpha)}}_{I} \left(\frac{\alpha_K}{R^\star}\right)^{\alpha/(1-\alpha)} \left[\bar{\lambda}_1 \bar{h}\right]^\psi \underbrace{\mathcal{H}(\tau)^{1-\psi}}_{III}$$

when $\theta = 0$.

I produces the conventional crowding-out effect of private capital by the environmental tax. II produces the health-saving effect. It is explained by the fact that pollution affects the health profile over the life-cycle. The health profile influences the efficient wage profile, which modifies saving.

So far, we have identified the mechanisms through which environmental taxation influences the economy when the life-cycle characteristic of the health profile is taken into account. To identify the specific role of the health profile, we now suppose a flat health profile. We assume that the health-status is the same for young and old individuals, that is $h_2 = h_1 = h^\star$ and therefore $\Delta_h^\star = 1$. Because the evolution of the health status is given by equation (3), we obtain the endogenous expression of the health status in the steady-state:[16]

$$h^\star = \frac{H(\bar{m})}{d(P^\star)} \tag{C.14}$$

Therefore, equation (C.10) with $\Delta_h^\star = 1$ defines the steady-state interest rate:

$$\bar{\lambda}_1^{-\theta} = \left(\frac{\psi}{1-\psi}\right) \frac{\beta R^\star - \frac{\alpha_K}{\alpha_L}(1+\beta)}{1 + \frac{\alpha_K}{\alpha_L}(1+\beta)} > 0 \tag{C.15}$$

From this expression, we obtain:

Proposition C.2. *In the presence of a flat health profile, the steady-state interest rate $R^\star$ is independent from the environmental tax τ whatever the technology of production.*

Proof. Straightforward from (C.15). □

In this case, there are only two channels of transmission of the environmental tax on final output leading to the crowding-out effect and the productivity effect. Therefore, the key element of the health-saving effect is the change in health over the life-cycle.

[16]Please note that a flat health profile does not mean an exogenous health status in the steady-state because it depends on $P^\star$, which is endogenous.