Reconsidering the impact of environment on long-run growth when pollution influences health and agents have a finite-lifetime

Xavier Pautrel*
xavier.pautrel@univ-nantes.fr

May 3, 2007

Abstract

Using an overlapping generation model *à la* Blanchard (1985) with human capital accumulation, we demonstrate that the influence of environment on optimal growth in the long-run may be explained by the detrimental effect of pollution on life expectancy. We also show that, in such a case, greener preferences are growth- and welfare-improving in the long-run even if the ability of the agents to learn is independent of pollution and utility is additively separable. Finally, we establish that a minimum environmental policy is required to obtain a sustainable equilibrium in the market economy and that it is possible to implement a win-win environmental policy.

Keywords : Growth; Environment; Overlapping generations; Human capital; Health.

---

*Université de Nantes, Nantes Atlantique Université, Laboratoire d'Économie de Nantes (LEN), Chemin de la Censive du Tertre, BP 81307, 44313 Nantes Cedex 3, France.

1 INTRODUCTION

Does the environment affect long-term growth? Do environmental issues modify the time devoted to education? Is it possible to implement a win-win environmental policy? Over the last decade, researchers have offered some partial answers to these questions. Nevertheless, their relevance remains topical, especially as we face uncurbed industrialization of economies, such as the economy of China, which challenges worldwide efforts for a cleaner environment.

The purpose of this article is to re-examine the link between environment and growth focusing on the influence of pollution on health. We argue that the effects of pollution on life expectancy may explain by themselves the influence of environment on optimal growth. This conclusion is contrary to some previous theoretical works that assumed that the influence of environment on health leads to a direct detrimental impact of pollution on educational activities.

In their investigations of the role of environment on long-term growth, some researchers have emphasized the impact of pollution on health. In dynamic models where the engine of growth is human capital accumulation, some of them argued that, by affecting health, pollution has a direct impact on long-term performances because it reduces the ability to learn (Gradus and Smulders (1993), van Ewijk and van Wijnbergen (1995), Vellinga (1999), Vellinga and Withagen (2001)). They also demonstrated that environment does not influence long-term accumulation of human capital if this direct impact of pollution on education is not taken into account. Even if the link between pollution and education sounds logical, we want to bring up two criticisms of their analysis. First, they did not model explicitly either the influence of pollution on health (although it is the key mechanism), or the way by which poor health may alter the ability to learn. Pollution is broadly introduced in the education sector as a simple component of the human capital depreciation (Gradus and Smulders (1993)) or as a variable which influences the productivity of educational activities (van Ewijk and van Wijnbergen (1995)). Microfoundations would be necessary to clarify the underlying mechanisms. Second, the impact of pollution on health is well-documented (see below) and it is unmistakable that health affects growth positively. [1] Nevertheless, this relation appears bi-directional and while the influence of education on health has been empirically established (see Grossman and Kaestner (1997)), there is lack of empirical work on the causality between health and education (see Ding et al. (2005)). [2]

Conversely, the fact that pollution shortens life expectancy is well-documented. In its 2002 report, the World Health Organization estimates that about 800,000 deaths and 7.9 million lost life-years worldwide are attributable to air pollution. This adverse effect is especially true of particulate matter (particles small enough to be inhaled in the lung) which causes "5% of trachea, bronchus and lung cancer, 2% of cardio-respiratory mortality and 1% of respiratory infections mortality globally." (WHO 2002, p.69) While the WHO estimates that two thirds of the time this burden occurs in Asian developing countries [Health Effects Institute (2004)], the adverse effect of ambient air pollution on life expectancy, especially in the long-term, has been extensively demonstrated in developed countries by studies conducted in Europe and North America (see Brunekreef and Holgate (2002)). For instance, Bell and Davis (2001) demonstrate that, during the London smog in 1952, 12,000 excess deaths occurred from December 1952 to February 1953 because of higher concentrations of SO_2 (The concentration level was 5 to 19 times above current regulatory standards). The authors also highlight that the mortality rates during this period were 50% to 300% higher than the previous year and that the effects are not only in the short-term but also in the long-term. Kunzli et al. (2000) calculate the net impact of pollution related to transport in Europe and show that in 1996, air pollution caused 5,600 cases of premature death in Austria and 31,700 cases in France for adults more than 30 years old. Valent et al. (2004) find that between 1.8% and 6.4% of deaths of children aged 0-4 years come from outdoor air pollution in Europe, while 4.6% of all deaths are attributable to indoor air pollution. In the USA, Pope et al. (2002) reveal that those who live in more polluted areas have significantly higher risks of lung cancer and cardiopulmonary mortality. Evans and Smith (2005) show the current and long-term effects of particulates on heart attacks and angina and demonstrate that long-term exposure to high ozone levels significantly shortens life. Moreover, for the largest 20 U.S. cities, Dominici et al. (2000) and Daniels et al. (2000) demonstrate that air pollution increases the risk of death from cardiovascular and respiratory causes, even at concentrations below regulatory limits and after accounting for statistical problems of the estimations. [3] Dominici et al. (2002) confirm these results for 88 U.S. cities: a 10 g/m^3 increase in particulate matter smaller than 10 microns increases mortality by 0.5%, and this increase is twice as high as the average in the Northeast region. Chay and Greenstone (2003) link air pollution to health and economic activity showing that a drop in economic activity which reduces the total suspended particulates in air of 1%, leads to a 0.35% decline in the infant mortality rate at the country level.

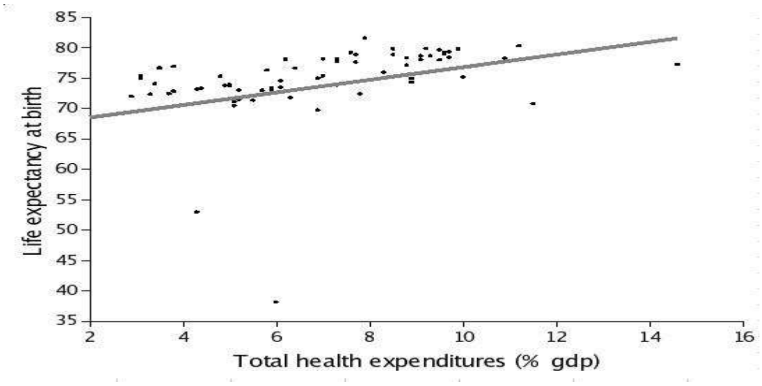
For water pollution, Valent et al. (2004) find that inadequate water and sanitation are responsible for 5.3% of deaths and 3.5% of disability-adjusted life years (DALYs) for young people aged 0-14 years in Europe. Several other studies link the presence of some pollutants in drinking water to the increase in cancer risk: tetrachloroethylene (PCE) and lung cancer in Massachusetts [Paulu et al. (1999)], arsenic and bladder cancer in Finland [Kurttio et al.

(1999)] and the use of chlorine for water treatment and bladder and rectal cancer in the United States [Morris (1995)]. Industrial or chemical pollution is also reported as increasing the cases of cancer for adults and children contributing to shorter life expectancy [Nadal et al. (2004), Chen and Liao (2005), Schuhmacher and Domingo (2006)].

In this article, we investigate the impact of pollution on life expectancy as the main channel of transmission of the relation between environment, health and growth, rather than assuming a direct detrimental effect of pollution on the ability to learn. For this purpose, we model explicitly the link between pollution and public health and its impact on the lifetime of the agents, assuming there is no direct impact of environment on schooling. We use an overlapping generations model *à la* Blanchard (1985) with environmental concerns. Long-run growth is driven by human capital accumulation *à la* Lucas (1988) and the lifetime of agents depends on public health which is influenced negatively by the level of pollution and positively by public health expenditures (see Figure 1 below). We study only the long-run balanced growth equilibrium.

Our results are threefold. First, although the environment does not affect individual education, we demonstrate that pollution always has a negative impact on optimal growth. Indeed, the accumulation of human capital at aggregate level is reduced by the loss of knowledge due to the vanishing

Figure 1: Life expectancy and total health expenditures for middle- and high-income countries, 2002



Source: World Development Indicators 2005.

of the dying generation. The rate at which a cohort vanishes depends on its life expectancy which is influenced by public health. When pollution is higher, despite the increase in public sanitary health expenditures, public health diminishes and the lifetime of agents as well. The vanishing of dying generations is faster and so the accumulation of human capital at aggregate level is lower. Furthermore, the time devoted to education in the long-run is influenced by pollution according to the value of the intertemporal elasticity of substitution of consumption. When this elasticity is lower than unity, a higher level of pollution increases the time devoted to education. The social planner wants to smooth consumption over time and he has the desire to compensate the detrimental effect of more pollution on his utility by increasing consumption in the future. Therefore he invests more in human capital accumulation.

Second, contrary to Vellinga (1999), we demonstrate that environmental care positively influences the rate of growth in the long-run, although preferences are additively separable and the individual accumulation of human capital is not affected by pollution. Furthermore, when agents have an intertemporal elasticity of substitution of the consumption lower than unity, greener preferences lead to a decrease in the time allocated to education while growth rate increases. We also establish that the growth-improving effect of greener preferences is always associated with a higher social welfare in the long-run balanced growth equilibrium.

Finally, studying the market equilibrium of the economy, we demonstrate that a minimum environmental policy is required to obtain a sustainable equilibrium with positive growth, and that it is possible to implement a win-win environmental policy.

The article is structured as follows. Section 2 gives the basic framework of our model and formalizes the link between pollution, health and the probability of death. Section 3 investigates the long-run balanced growth path (BGP) equilibrium of the centralized economy. Section 4 examines the impact of environmental care on the optimal growth in the long-run. Section 5 deals with environmental policy in a market equilibrium and section 6 draws this article to a conclusion.

2 THE ECONOMY'S STRUCTURE

Let us consider an overlapping generations model *à la* Blanchard (1985) with human capital accumulation and environmental concerns. Time is continuous. Each individual born at time s faces a constant probability of death per unit of time $\lambda_s \geq 0$. Consequently, his life expectancy is $1/\lambda_s$. When λ_s increases, the horizon of the economy becomes shorter. At time s, a cohort of size λ_s is born. This cohort has a size equal to $L_{s,t} \equiv \lambda_s e^{-\lambda_s (t-s)}$ at time t. The constant population is equal to $\int_{-\infty}^{t} L_{s,t} ds$ at time t. There are insurance companies and there is no bequest motive.

Contrary to Blanchard (1985), we assume that the probability of death for an agent born at time s depends negatively on the public health in the economy when he is born ε_s. To simplify we pose $\lambda_s = \varepsilon_s^{-1}$. Following the introduction, we consider that public health at time s is influenced negatively by the net flow of pollution and positively by the part of public health expenditures in GDP: [4]

$$\varepsilon_s = \frac{\beta \theta_s}{\delta \mathcal{P}_s^{\psi}} \tag{1}$$

where $\mathcal{P}$ is the net flow of pollution (see below) and θ is the part of the aggregate final output that the government uses to publicly provide public-health services. $\beta > 0$ is the productivity of the health sector, δ is a positive parameter and $\psi > 0$ measures the influence of pollution on public health.

The expected utility function of an agent born at $s \leq t$ is:

$$\int_{s}^{\infty} U\left(c_{s,t}, \mathcal{P}_t\right) e^{-(\rho+\lambda_s)(t-s)} dt \tag{2}$$

with

$$U\left(c_{s,t}, \mathcal{P}_t\right) = \begin{cases} \dfrac{[c_{s,t}\mathcal{P}_t^{-\phi}]^{1-1/\sigma} - 1}{1-1/\sigma} & \sigma \neq 1, \\ \\ \ln c_{s,t} - \phi \ln \mathcal{P}_t & \sigma = 1, \end{cases} \tag{3}$$

where $c_{s,t}$ denotes consumption in period t of an agent born at time s, $\rho \geq 0$ is the rate of time preference and ϕ measures the weight in utility attached to the environment, that is environmental care. σ is the elasticity of intertemporal substitution.

The representative agent can increase his stock of human capital by devoting time to schooling, according to Lucas (1988):

$$\dot{h}_{s,t} = B\left[1 - u_{s,t}\right] h_{s,t} \tag{4}$$

where B is the efficiency of schooling activities, $u_{s,t} \in [0,1]$ is the part of human capital allocated to productive activities at time t for the generation born at s and $h_{s,t}$ is the stock of human capital at time t of an individual born at time s. Note that we make no assumption about the influence of pollution on individual human capital accumulation.

Due to the simple demographic structure, all individual variables are additive across individuals. Consequently, the aggregate consumption equals

$$C_t = \int_{-\infty}^{t} c_{s,t} L_{s,t} ds,$$

the aggregate human capital is

$$H_t = \int_{-\infty}^{t} H_{s,t} ds, \tag{5}$$

where $H_{s,t} = h_{s,t} L_{s,t}$ is the stock of human capital at time t of the living cohort born at s. We assume that the human capital of an agent born at current date, $h_{t,t}$, is inherited from the dying generation. [5] Because the mechanism of intergenerational transmission of knowledge is complex, [6] we make the simplifying assumption that the human capital inherited from the dying generation is a constant part of the aggregate level of human capital such that $h_{t,t} = \eta H_t$ with $\eta \in]0, 1[$.

The aggregate production function is defined by:

$$Y_t = K_t^{\alpha} \left[\int_{-\infty}^{t} u_{s,t} H_{s,t} ds \right]^{1-\alpha}, \qquad 0 < \alpha < 1 \tag{6}$$

with Y_t being the aggregate final output. K_t is the aggregate stock of physical capital and $\int_{-\infty}^{t} u_{s,t} H_{s,t} ds$ is the amount of the aggregate stock of human capital used in production.

Following Gradus and Smulders (1993), pollution flow is assumed to increase with the stock of physical capital K and reduces with abatement activities A:

$$\mathcal{P}_t = \left[\frac{K_t}{A_t} \right]^{\gamma}, \qquad \gamma > 0 \tag{7}$$

Abatement activities use final output so the final market clearing condition is:

$$(1-\theta_t)Y_t = C_t + \dot{K}_t + \xi A_t, \qquad \xi > 0 \tag{8}$$

3 OPTIMAL GROWTH AND POLLUTION ALONG THE BALANCED GROWTH PATH

In this section, we investigate the influence of environment on the optimal growth in the long-run balanced growth equilibrium defined as a steady-state where variables K, A, Y, C, and H grow at a common endogenous rate $g^\star$ and where the intersectoral allocation of human capital u and the part of the aggregate final output used to provide public-health services θ are constant.

Differentiating (5) with respect to time and recalling that $H_{s,t} = h_{s,t}L_{s,t}$ gives $\dot{H}_t = \int_{-\infty}^{t} \left[\dot{h}_{s,t}L_{s,t} + h_{s,t}\dot{L}_{s,t}\right] ds + h_{t,t}L_{t,t}$. Because $L_{s,t} = \lambda_s e^{-\lambda_s(t-s)}$, we obtain $\dot{H}_t = \int_{-\infty}^{t} \dot{h}_{s,t}L_{s,t}ds - \int_{-\infty}^{t} \lambda_s h_{s,t}L_{s,t}ds + h_{t,t}L_{t,t}$. Finally using (4) and the fact that we defined $h_{t,t} = \eta H_t$ with $\eta \in]0,1[$ (Cf. page 11), the aggregate accumulation of human capital is:

$$\dot{H}_t = \int_{-\infty}^{t} B\left[1-u_{s,t}\right] H_{s,t}ds - \int_{-\infty}^{t} \lambda_s H_{s,t}ds + \eta\lambda_t H_t \tag{9}$$

The first term in the right-hand side of the equation represents the increase in the aggregate human capital due to the investment of each generation $s \leq t$ in education at time t. The second term in the right-hand side of the equation captures the fact that a part λ_s of the living cohort born at s with a stock of human capital equal to $H_{s,t}$ vanishes reducing growth by $\int_{-\infty}^{t} \lambda_s H_{s,t}ds$

when all generations are aggregated. The last term in the right-hand side of the equation captures the fact that at the same time, a new cohort of size λ_t appears, adding $\lambda_t h_{t,t}$ to growth, with $h_{t,t} = \eta H_t$ and $\eta \in]0, 1[$ (Cf. page 11). Consequently, the aggregate accumulation of human capital is reduced by a term $\int_{-\infty}^{t} \lambda_s H_{s,t} ds - \eta \lambda_t H_t$ which represents the loss of human capital due to the vanishing of dying generation net from the intergenerational transmission of human capital. [7] Because this term depends on the probability of death (λ_s for $s \leq t$), which is also the inverse of the lifetime of agents, and because the lifetime of agents is influenced by the flow of pollution (equation 1), the environment influences accumulation of human capital at the aggregate level although it has no impact on the ability to learn. [8]

The objective of the social planner consists in maximizing the social welfare function taking into account the intertemporal evolution of the aggregate physical capital and the aggregate human capital. We can write the program as follows: [9]

$$\begin{array}{rl}
\max_{\substack{c_{s,t}, u_{s,t}, A_t, \theta_t \\ K_t, H_t, H_{s,t}}} & \displaystyle\int_0^\infty \left\{ \int_{-\infty}^{t} U[c_{s,t}, \mathcal{P}_t] L_{s,t} ds \right\} e^{-\rho t} dt \\
\text{s.t.} & \dot{K}_t = (1-\theta_t) K_t^{\alpha} [\int_{-\infty}^{t} u_{s,t} H_{s,t} ds]^{1-\alpha} - \int_{-\infty}^{t} c_{s,t} L_{s,t} ds - \xi A_t \\
& \dot{H}_t = \int_{-\infty}^{t} B[1-u_{s,t}] H_{s,t} ds - \int_{-\infty}^{t} \lambda_s H_{s,t} ds + \eta \lambda_t H_t \\
& H_t = \int_{-\infty}^{t} H_{s,t} ds \\
& \mathcal{P}_t = (K_t/A_t)^{\gamma} \\
& \lambda_t = \dfrac{\delta \mathcal{P}_t^{\psi}}{\beta \theta_t} \\
& K_t > 0, H_t > 0, K_0 \text{ and } H_0 \text{ given,}
\end{array} \tag{10}$$

with $U\left(c_{s,t}, \mathcal{P}_t\right)$ defined by equation (3).

The resolution of this program gives that $\lambda_s = \lambda_t$, $u_{s,t} = u_t$ and $c_{s,t} = c_t$ at the optimum. [10] It also gives the optimal allocation of human capital to production along the BGP

$$u^\star = \frac{\sigma\rho}{B} + (1-\sigma)\frac{B - \Lambda(\mathcal{P}^\star)(1-\eta)}{B}, \qquad \forall\ \sigma \tag{11}$$

where $\Lambda(\mathcal{P}^\star) = \frac{2(1-\alpha)\delta}{\beta\left[-(\sigma-\alpha)\varphi + \sqrt{(\sigma-\alpha)^2\varphi^2 + 4(1-\alpha)^2\varphi/\mathcal{P}^{\star\psi}}\right]}$ increases with the value of the pollution flow in the long run $\mathcal{P}^\star$ given by:

$$\gamma\left(\frac{1-\alpha}{\alpha}\right)\left[\phi + \frac{(1-\eta)\Lambda(\mathcal{P}^\star)}{\rho}\right]\left[B + \mathcal{P}^{\star -1/\gamma} - (1-\eta)\Lambda(\mathcal{P}^\star)\right] + \gamma\phi\rho - \xi\mathcal{P}^{\star -1/\gamma} = 0 \tag{12}$$

Along the balanced growth path the net flow of pollution $\mathcal{P}^\star$ is constant which verifies that the environmental quality is constant in the long run.

Finally, the optimal rate of growth along the BGP is

$$g^\star = \sigma B - \sigma\rho - \sigma\Lambda(\mathcal{P}^\star)(1-\eta)$$

It is negatively influenced by the net flow of pollution whatever the value of the intertemporal elasticity of substitution of consumption.

4 ENVIRONMENTAL CARE AND LONG-RUN GROWTH

Do greener preferences lead to a higher or a lower optimal growth in the long-run? Due to the complexity of the expressions of $\mathcal{P}^\star$ (equation 12), we use numerical simulations to answer this question. We calibrate the model to obtain realistic values of the growth rate of GDP and the probability of death for the US economy. From the *World Development Indicators 2005* by the World Bank, life expectancy was 77.4 years in 2003, the growth rate was 3.3% during the period 1990-2002 and a public health expenditures as percentage of GDP was 6.55%. Since the expected lifetime is the reverse of the probability of death per unit of time λ, we want λ to be close to $1/77.4 = 0.0129$. We adjust other variables to obtain such values for our benchmark case.

Table 1 summarizes the benchmark value of parameters and Table 2 summarizes the exercise of comparative statics for log utility.

ϕ	α	ξ	η	δ	ψ	β	ρ	B	γ
0.01	0.3	0.0075	0.85	0.025	2	120	0.065	0.1	0.3

Table 1. Benchmark value of parameters

	Benchmark	$\phi = 0.007$	$\phi = 0.1$	$B = 0.15$	$\xi = 0.015$
g	3.31%	3.30%	3.36%	8.33%	3.28%
$\mathcal{P}$	1.1166	1.1318	0.8428	1.0155	1.3168
λ	0.0128	0.0130	0.0096	0.0116	0.0151
u	0.65	0.65	0.65	0.43	0.65
Y/K	0.3514	0.3506	0.3785	0.5277	0.3542
C/K	0.3060	0.3054	0.3259	0.4276	0.3070
H/K	0.3453	0.3442	0.3840	0.9259	0.3493
A/K	0.6923	0.6618	1,7682	0.9501	0.3996
θ	0.0203	0.0205	0.0153	0.0185	0.0239
W	7.81	7.80	8.20	19.70	7.70

Table 2. Numerical estimations for log utility along the BGP

The third and fourth columns of table 2 highlight that environmental care influences the long-term growth rate. This result is different from the result obtained by Vellinga (1999) who demonstrated that growth is not influenced by environment when pollution does not affect the ability of the individual to learn and preferences are additive. When ϕ increases (fourth column), the weight of the net flow of pollution increases in utility. Consequently, the government decides to increase their abatement expenditures to the detriment of physical capital. This leads to a decrease in the net flow of pollution. Consequently, public health improves and the probability of death is reduced, increasing the aggregate human capital accumulation although the time allocated to education (u) remains unchanged. The BGP growth rate rises, as well as the ratios H/K, Y/K, C/K.

The fifth column shows that an increase in the effectiveness of education (B) encourages the social planner to allocate more resources to education and consequently $u^\star$ drops. This leads to a decrease in the rate of returns to physical capital. Consequently, production becomes less intensive in terms of physical capital and pollution falls. A lower level of pollution leads to improved public health and a lower probability of death. This change contributes, with the increase in B, to a substantial rise of the long-term rate of growth. The sixth column emphasizes that a deterioration in the technology of abatement (ξ the part of output used for abatement increases) leads to higher pollution. This means a greater probability of death and thus a lower long-term rate of growth. The crowding-out effect of abatement activities increases.

Table 2 also reports the values of social welfare with respect to changes in the value of parameters. [11] More environmental care leads to greater social welfare due to the reduction in the net flow of pollution and the increase in the growth rate of output. In the same way, a more efficient education sector (B is higher) leads to a higher growth rate and a lower level of net pollution and so implies greater social welfare (fifth column). [12]

Using parameter value from Table 1, we also simulate the economy for different values of the intertemporal elasticity of substitution σ.

	Benchmark	$\phi = 0.007$	$\phi = 0.1$	$B = 0.15$	$\xi = 0.015$
g	2.47%	2.46%	2.51%	6.22%	2.42%
$\mathcal{P}$	1.1295	1.1458	0.8421	1.0426	1.3326
λ	0.0137	0.0139	0.0102	0.0137	0.0162
u	0.7324	0.7323	0.7337	0.5716	0.7314
Y/K	0.3499	0.3491	0.3780	0.5235	0.3524
C/K	0.3134	0.3128	0.3341	0.4462	0.3142
H/K	0.3046	0.3036	0.3396	0.6941	0.3082
A/K	0.6664	0.6352	1.7731	0.8702	0.3840
θ	0.0193	0.0196	0.0144	0.0165	0.0228
W	5.23	5.83	6.20	14.72	5.74

Table 3. Numerical estimations for $\sigma = 0.75$

	Benchmark	$\phi = 0.007$	$\phi = 0.1$	$B = 0.15$	$\xi = 0.015$
g	4.33%	4.32%	4.38%	10.88%	4.28%
$\mathcal{P}$	1.0983	1.1120	0.8425	0.9662	1.2945
λ	0.0116	0.0117	0.0089	0.0087	0.0137
u	0.5502	0.5503	0.5490	0.2659	0.5512
Y/K	0.3535	0.3527	0.3795	0.5357	0.3567
C/K	0.2971	0.2965	0.3161	0.4065	0.2985
H/K	0.4114	0.4101	0.4564	1.5414	0.4161
A/K	0.7314	0.7018	1.7707	1.1213	0.4229
θ	0.0217	0.0219	0.0167	0.0224	0.0255
W	10.22	10.21	10.62	25.78	10.10

Table 4. Numerical estimations for $\sigma = 1.3$

Whatever the value of σ, our results remain valid: an increase in environmental care leads to a lower value of pollution while the rate of growth is higher in the long-run. When $\sigma < 1$, a greater ϕ leads to a higher allocation of human capital to production for the reasons explained previously, while the long-term rate of growth increases.

We also report the values of social welfare. The social welfare improves with greener preferences and higher efficiency of schooling activities.[12]

5 MARKET EQUILIBRIUM AND ENVIRONMENTAL POLICY

In this section, we investigate the effect of a pollution tax on the growth rate of the market equilibrium. In the economy, there are three externalities. The first one comes from the detrimental effect of pollution on utility. The second one arises via the channel through which pollution affects the economy: public health is negatively influenced by pollution. The third one comes from the fact that aggregate human capital accumulation is influenced by intergenerational transmission of knowledge but individual human capital accumulation is not. In a market economy, final producers do not internalize the negative impact of their pollution flow either on utility or on public health. Therefore, with no public intervention, they would pollute so much that the environmental quality would decline to unsustainable low levels. Environmental policy is needed to prevent such an occurrence. Furthermore, in his decision to educate, an individual does not take into account the effect of the intergenerational transmission of knowledge in his returns to education and so invests insufficiently in education. Consequently, the government must also subsidize education in order to encourage agents to internalize the intergenerational transmission of knowledge.

Let us consider a market economy. As in the previous section, the government uses a part θ of the aggregate final output to publicly provide health services. We assume that this amount is exogenous. [13] The final market clearing condition is always given by equation (8).

Furthermore, the government also implements an environmental policy which consists of taxing the net flow of pollution by firms and transferring to them the fruit of the taxes to fund their abatement activities.

Consequently, in the market economy, firms under perfect competition pay a pollution tax on their net pollution $\mathcal{P}_t$ and they choose their abatement activities A_t (whose cost equals ξA_t) and the amount of factors which maximize their profits $\pi_t = Y_t - r_t K_t - w_t \left[\int_{-\infty}^{t} u_{s,t} H_{s,t} ds\right] - \vartheta_t \mathcal{P}_t - \xi A_t + T_t^p$ where ϑ_t is the pollution tax rate and T_t^p denotes transfers from the public sector with $T_t^p = \vartheta_t \mathcal{P}_t$. Firms take as given these transfers and pay each production factor at its marginal productivity to maximize profit:

$$r_t = \alpha \frac{Y_t}{K_t} - \vartheta_t \gamma \frac{\mathcal{P}_t}{K_t} \tag{13}$$

$$w_t = (1-\alpha) K_t^{\alpha} \left[\int_{-\infty}^{t} u_{s,t} H_{s,t} ds\right]^{-\alpha} \tag{14}$$

$$\xi A_t = \vartheta_t \gamma \mathcal{P}_t \tag{15}$$

From equations (7) and (15), we have $\mathcal{P}_t = \left[\chi \frac{\vartheta_t}{K_t}\right]^{-\gamma/(1+\gamma)}$ with $\chi \equiv \gamma/\xi$. Therefore, from (1) and because we assumed $\lambda_t = \varepsilon_t^{-1}$, the probability of death is a function of the ratio ϑ_t/K_t. As we will demonstrate on page 25, the environmental tax rate which internalizes all the environmental externalities (the "*optimal*" tax rate) evolves at the same rate as the physical capital. [14] Intuitively, ϑ_t increases over time to encourage firms to increase abatement activities to limit pollution which rises with the physical capital stock. Consequently, we define $\tau \equiv \vartheta_t/K_t$, the environmental tax normalized by the physical capital and we write:

$$\mathcal{P} = [\chi\tau]^{\frac{-\gamma}{1+\gamma}} \tag{16}$$

$$\lambda = \frac{\delta \left[\chi\tau\right]^{\frac{-\gamma\psi}{1+\gamma}}}{\beta\theta} \equiv \mathcal{L}(\underset{-}{\tau}) \tag{17}$$

Because τ is fixed by the government and therefore has no transitional dynamics (Oueslati (2002)), $\mathcal{P}$ and λ are independent of time.

Households face the following budget constraint:

$$\dot{a}_{s,t} = \left[r_t + \lambda\right] a_{s,t} + u_{s,t}h_{s,t}w_t - c_{s,t} - T^H_{s,t} + (1 - u_{s,t})h_{s,t}w_t z^H \tag{18}$$

where $a_{s,t}$ is the financial wealth in period t and ω_t represents the wage rate per effective unit of human capital $u_{s,t}h_{s,t}$. z^H denotes the rate of the education subsidy applied to the labor input in the education sector by the government to foster schooling investment. $T^H_{s,t}$ is a lump-sum tax used to finance education subsidy.

The representative agent chooses the time path for $c_{s,t}$ and his working time $u_{s,t}$ by maximizing (2) subject to (4) and (18). It gives the consumption at time t of an agent born at time s:

$$c_{s,t} = \Delta_t^{-1} \left[a_{s,t} + \omega_{s,t}\right] \tag{19}$$

where $\omega_{s,t} \equiv \int_t^\infty \left[u_{s,\nu}h_{s,\nu}w_\nu\right] e^{-\int_t^\nu [r_\zeta + \lambda] d\zeta} d\nu$ is the present value of lifetime earning and

$$\Delta_t \equiv \int_t^\infty e^{-(\sigma\rho+\lambda)(\nu-t)-(1-\sigma)\int_t^\nu r_\mu d\mu} d\nu$$

It also gives:

$$\frac{\dot{w}_t}{w_t} + \frac{B}{1 - z^H} = r_t + \lambda \tag{20}$$

The rate of returns to human capital is equal to the effective rate of interest. It is independent of s, therefore all individuals allocate the same effort to schooling: $u_{s,t} = u_t$.

The aggregate consumption equals

$$C_t = \int_{-\infty}^{t} c_{s,t} \lambda e^{-\lambda(t-s)} ds = \Delta_t^{-1} \left[K_t + \Omega_t \right] \tag{21}$$

with $\Omega_t \equiv \int_{-\infty}^{t} \omega_{s,t} \lambda e^{-\lambda(t-s)} ds$, and the aggregate stock of physical capital is defined by

$$K_t = \int_{-\infty}^{t} a_{s,t} \lambda e^{-\lambda(t-s)} ds \tag{22}$$

Differentiating (21) with respect to time and using the expression of dK_t/dt and $d\Omega_t/dt$ gives:

$$\dot{C}_t = \sigma \left[r_t - \rho \right] C_t - \lambda \Delta_t^{-1} K_t \tag{23}$$

Finally, using (20), (14) and the fact that $\int_{-\infty}^{t} u_{s,t} H_{s,t} ds = u_t H_t$, we obtain:

$$\dot{u}_t / u_t = \dot{K}_t / K_t - \dot{H}_t / H_t - \alpha^{-1} \left[r_t + \lambda - \frac{B}{1 - z^H} \right] \tag{24}$$

Using previous results, we can write the dynamics of the model as:

$$\begin{aligned}
\dot{x}_t = &\ \left\{\left[\alpha\sigma-(1-\theta)\right](b_t u_t)^{1-\alpha}+(1-\sigma)\xi\left[\chi\tau\right]^{1/(1+\gamma)}-\sigma\rho-\mathcal{L}(\tau)\Delta_t^{-1}x_t^{-1}+x_t\right\}x_t \\
\dot{b}_t = &\ \left\{B\left[1-u_t\right]-(1-\eta)\mathcal{L}(\tau)-(1-\theta)(b_t u_t)^{1-\alpha}+x_t+\xi\left[\chi\tau\right]^{1/(1+\gamma)}\right\}b_t \\
\dot{u}_t = &\ \left\{\alpha^{-1}\left[\frac{B}{1-z^H}-\mathcal{L}(\tau)\right]-(b_t u_t)^{1-\alpha}+\alpha^{-1}\xi\left[\chi\tau\right]^{1/(1+\gamma)}-\dot{b}_t/b_t\right\}u_t \\
\dot{\Delta}_t = &\ -1+\left[(1-\sigma)\alpha(b_t u_t)^{1-\alpha}-(1-\sigma)\xi\left[\chi\tau\right]^{1/(1+\gamma)}+\sigma\rho+\mathcal{L}(\tau)\right]\Delta_t
\end{aligned} \tag{25}$$

where $x_t \equiv C_t/K_t$, $b_t \equiv H_t/K_t$ and $\mathcal{L}(\tau) \equiv \frac{\delta}{\beta\theta}\left[\chi\tau\right]^{\frac{-\gamma\psi}{1+\gamma}}$.

Along the balanced growth path, C, K, H, A and Y evolve at a common rate and the allocation of human capital across sectors is constant. Consequently, from (21), Δ must be constant and $\dot{x}=\dot{b}=\dot{u}=\dot{\Delta}=0$. From the third equation of system (25):

$$\alpha\left(b_d^\star u_d^\star\right)^{1-\alpha}-\xi\left[\chi\tau\right]^{\frac{1}{1+\gamma}}=\frac{B}{1-z^H}-\mathcal{L}(\tau), \tag{26}$$

where $b_d^\star$ and $u_d^\star$ are respectively the BGP value of u and b in the market economy. The private returns to physical capital accumulation equals the private returns to education.

Subtracting the first and the second equation of (25) and using the fourth equation, for $\dot{x}=\dot{b}=\dot{u}=\dot{\Delta}=0$, gives the expression of x. Equalizing to the expression of x given by the second equation of (25) for $\dot{b}=0$, and using

(26) enables us to express the implicit value of $u_d^\star$:

$$\Gamma(u_d^\star) \equiv \left[B \left(\frac{\sigma}{1 - z^H} - 1 + u_d^\star \right) + (1 - \sigma - \eta)\mathcal{L}(\tau) - \sigma\rho \right] \times \\ \left\{ \left[u_d^\star + \frac{\mathcal{A} + z^H}{1 - z^H} \right] B - \mathcal{L}(\tau) \left[\mathcal{A} + \eta \right] + \mathcal{A}\xi \left[\chi\tau \right]^{\frac{1}{1+\gamma}} \right\} \\ - \mathcal{L}(\tau) \left[\sigma\rho + \sigma\mathcal{L}(\tau) + (1 - \sigma) \frac{B}{1 - z^H} \right] = 0 \quad (27)$$

with $\mathcal{A} \equiv \alpha^{-1}(1 - \theta) - 1$.

This equality defines a unique $u_d^\star \in]0, 1[$ which decreases with τ, for an intertemporal elasticity of substitution that is sufficiently high ($\sigma \geq 1 - \eta$), a part of public health expenditures in GDP that is sufficiently low ($\theta \leq 1 - \alpha$) and $\tau \in]\underline{\tau}, \bar{\tau}[$. [15] This last condition means that the pollution tax must be higher than a minimal value in order to encourage agents to invest in human capital accumulation.

Finally, the growth of the market economy along the BGP is:

$$g_d^\star = B \left[1 - u_d^\star(\tau) \right] - (1 - \eta) \frac{\delta}{\beta\theta} \left[\chi\tau \right]^{\frac{-\gamma\psi}{1+\gamma}}.$$

When $\sigma \geq 1 - \eta$ and $\theta \leq 1 - \alpha$, the BGP rate of growth in the market economy increases with τ: environmental policy has a positive impact because it reduces pollution, so it increases health and the returns to education and therefore it fosters human capital accumulation. Therefore, it is possible to implement a win-win environmental policy in our framework. Nevertheless, the environmental tax rate must be higher than $\hat{\tau} > \underline{\tau}$ to have $g_d^\star > 0$. Consequently, a minimum environmental policy is required to obtain a sustainable equilibrium in the market economy.

We still must examine the optimal environmental policy that the government may implement to correct the externalities in the market economy. To do so, we use numerical simulations and we compare them to the optimal results found in section 4. We assume that the government chooses public health expenditures internalizing the external effect of pollution on health, so θ is fixed at its optimal value.

We define the optimal environmental tax as a pollution tax that internalizes environmental externalities. To obtain the expression for this tax, we equalize the expressions of abatement in the market economy (equation 15) and in the centralized economy:

$$\vartheta_t^{op} = K_t \left[\chi \mathcal{P}^{\star 1+\gamma}\right]^{-1} \tag{28}$$

with $\mathcal{P}^{\star}$ the level of pollution in the long run in the centralized economy given by equation (12). The optimal tax rate evolves like the current stock of physical capital to encourage firms to increase abatement activities to limit pollution which rises with the physical capital stock. Using our notation, we have:

$$\tau^{op} = \left[\chi \mathcal{P}^{\star 1+\gamma}\right]^{-1}$$

which is constant.

In table 5, we report the results of numerical simulations for the market economy with the optimal environmental tax and no education subsidy ($z^H = 0$), and we compare these results with the optimal solution.

	$\sigma = 1$		$\sigma = 0.75$		$\sigma = 1.3$	
	central.	*market*	*central.*	*market*	*central.*	*market*
τ^{op}		0.0155		0.0148		0.0166
g	3.30%	1.86%	2.47%	1.18%	4.33%	2.75%
$\mathcal{P}$	1.1166	1.1166	1.1295	1.1295	1.0983	1.0983
λ	0.0128	0.0128	0.0137	0.0137	0.0116	0.0116
u	0.65	0.7948	0.7324	0.8611	0.5502	0.7080
Y/K	0.3514	0.3079	0.3499	0.3042	0.3535	0.3129
C/K	0.3060	0.2779	0.3134	0.2815	0.2971	0.2732
H/K	0.3453	0.2339	0.3046	0.2121	0.4114	0.2687
A/K	0.6923	0.6923	0.6664	0.6664	0.7314	0.7314
θ	0.0203	0.0203	0.0193	0.0193	0.0217	0.0217
W	7.81	4.39	5.23	2.62	10.22	7.19

Table 5. Numerical estimations for the optimal environmental policy

Whatever the value of the intertemporal elasticity of substitution, the optimal environmental policy enables the level of pollution, the probability of death and public health expenditures to attain their optimal levels in the market economy. Pollution tax encourages firms to reduce pollution by increasing their abatement activities up to the centralized level, accounting for both the detrimental effect of their production on the environment and the disutility of pollution.

Nevertheless, the growth rate of the economy remains lower than its optimal value because the environmental policy does not account for the externality of the intergenerational transmission of knowledge on the aggregate accumulation of human capital. In the market economy, each individual integrates into his decision of education the influence of health in his lifetime (see the right-hand side of equation 26), but he does not integrate the effect of intergenerational transmission of knowledge: the social returns to education are higher than the private returns due to this intergenerational transmission of knowledge. Therefore, agents in the market economy invest less in education than agents in the centralized economy. The production is relatively more intensive in physical capital, so the returns to investment are lower and more foregone output is required to attain the optimal abatement intensity A/K. This fact contributes to reduced physical-capital accumulation and growth.

When the government fixes the education subsidy z^H such that the allocation of human capital in the production sector in the market economy (given by equation (27)) and in the centralized economy (given by equation (11)) are the same, the market equilibrium replicates the centralized equilibrium. [16]

6 CONCLUDING REMARKS

Our goal was to investigate the link between environment and growth focusing on the impact of pollution on health. Contrary to some previous works, we did not assume that the effect of environment on health leads to a direct impact of pollution on education. Rather, we argued—and demonstrated—that the detrimental influence of pollution on life expectancy is, by itself, a channel of transmission between environment, health and optimal growth in the long-run.

We used an overlapping generations model *à la* Blanchard (1985) assuming that the probability of death depends negatively on public health and that public health is influenced negatively by pollution and positively by public-health expenditures. We studied only the steady state and we demonstrated that pollution reduces the optimal rate of growth while the environment does not influence the individual accumulation of human capital. Pollution is responsible for deteriorating public health. This increases the probability of death in the economy, even if the social planner increases health expenditures in response to the lower quality of environment. Therefore, the replacement of generations becomes more frequent and the loss of knowledge due to this replacement grows, reducing the aggregate human capital accumulation and the growth rate of the economy.

In contrast to Vellinga (1999), we also demonstrated that greener preferences affect the optimal rate of growth in the long-term, although individual accumulation of human capital is independent of environment and preferences are separable. Furthermore, we showed that the time devoted to education is influenced by the level of pollution when the intertemporal elasticity of substitution of the consumption is not unity. For an elasticity lower than one, greener preferences lead to lower investment in education but nevertheless to a higher growth rate. We also established that in all cases, greener preferences are growth- and welfare-improving in the long-run, because they lead to a lower level of pollution, that is a lower probability of death which limits the replacement of generations and therefore fosters growth. Finally, by studying the equilibrium of the market economy, we demonstrated that a minimum environmental policy is required to obtain a sustainable equilibrium in the market economy and that it is possible to implement a win-win environmental policy.

The simplicity of our framework calls for further theoretical investigations especially to enrich the function of public health. It also offers other tools for public authorities to curve pollution and its detrimental effects on growth. These are tools which must be studied more precisely. This could give some direction for further research.

Acknowledgements

I would like to thank two anonymous referees and especially the associate editor Cees Withagen for helpful comments that helped improve this article. I also benefited from discussions with Pascal Belan. I finally thank Natasha Noy for her careful proofreading. The usual disclaimer applies.

NOTES

1. See López-Casanovas et al. (2005) for theoretical analysis and policy implications. See Bloom and Canning (2005) and references therein for empirical evidence.

2. Moreover, existing studies on the causality between health and education examine the effect of children's health on schooling performances in special cases: structural health problems like diseases or poor nutrition in developing countries (Mayer-Foulkes (2005)), obesity and depression in developed countries (see references in Ding et al. (2005)). How can we extrapolate the positive impact of health on education found in these studies to the situation where pollution is to blame for bad health in developed countries?

3. See Dominici et al. (2003) and Koop and Tole (2004) for a discussion about the statistical problems in evaluating the impact of air pollution on mortality rate.

4. We follow empirical studies which use in their estimations expenditures in health as a percentage of GDP rather than the amount of expenditures in health (see Currais and Rivera (1999), Currais and Rivera (2003) for example). Figure 1 page 7 gives an empirical evidence.

5. This assumption is not crucial for our results. Assuming that $h_{t,t}$ is exogenous would give the same qualitative results.

6. In the literature, intergenerational transmission of human capital is explained either by the parents' genetic characteristics, or by the parents' education and behaviour which influence children's schooling. Nevertheless the empirical evidence is not clear-cut. Controlling for genetic components, Behrman and Rosenzweig (2002) and Plug (2004) find no significant impact of a mother's schooling on her children's education. Taking into account historical changes in compulsory schooling laws to identify the causal environmental effect of parent's schooling, Oreopoulos et al. (2003) and Chevalier (2004) find a positive effect while Black et al. (2003) find no significant impact.

7. When population is growing, we have the same rational. The rest of the model is not modified qualitatively, but aggregate variables integrate the evolution of the population. See details in the separate Mathematical Appendix available on my website.

8. In the Mathematical Appendix, we demonstrate that $\lambda_s = \lambda_t$ and $u_{s,t} = u_t$ at the optimum. Consequently, the aggregate accumulation of human capital

may be written as $\dot{H}_t = B\,[1-u_t]\,H_t - (1-\eta)\lambda_t H_t$, with $\eta \in \,]0,1[$. A higher probability of death means a higher frequency at which a cohort vanishes and so a greater net loss. It reduces $\dot{H}_t$ for a given effort of education u_t. Consequently, pollution negatively affects the accumulation of aggregate human capital at the optimum.

9. All the demonstrations are documented in a separate Mathematical Appendix available on my website.

10. Note that none of the two corner solutions for u can be an equilibrium. See the Mathematical Appendix.

11. Social welfare is computed from equation (A.12) in the Mathematical Appendix assuming that the economy begins along the BGP. Consequently $C_t = C_0 e^{g^\star t}$ with $C_0 = 1$:

$$W = \int_0^\infty \ln[e^{g^\star t}\mathcal{P}^{\star -\phi}]e^{-\rho t}dt = \frac{g^\star/\rho - \phi \ln \mathcal{P}^\star}{\rho}, \qquad \sigma = 1,$$

$$W = \int_0^\infty \frac{[e^{g^\star t}\mathcal{P}^{\star -\phi}]^{1-1/\sigma} - 1}{1-1/\sigma} e^{-\rho t}dt = \frac{\mathcal{P}^{\star -\phi(1-1/\sigma)}\left[\rho - (1-1/\sigma)g^\star\right]^{-1} - 1/\rho}{1-1/\sigma}, \qquad \sigma \neq 1$$

12. We study only the BGP and neglect transitional gains or losses when moving from one steady state to the other.

13. In the Mathematical Appendix, we demonstrate that if the government chooses θ at its optimal level, all the results found in this section remain valid.

14. We use the term "*optimal*", but the tax imposed by the government is a second-best tax. We thank an anonymous referee for highlighting this point to us.

15. For $\sigma < 1-\eta$ and $\theta > 1-\alpha$, the impact of τ on $u_d^\star$ is not clear-cut, so we do not investigate this case.

16. When $\sigma = 1$, $z^H = 0.1237$ (with $\tau^{op} = 0.0155$) enables the market economy to replicate the centralized economy. Similarly, when $\sigma = 0.75$, $z^H = 0.1430$ (with $\tau^{op} = 0.0148$) and when $\sigma = 1.3$, $z^H = 0.1060$ (with $\tau^{op} = 0.0166$).

REFERENCES

Behrman, J. and Rosenzweig, M. (2002). Does increasing women's schooling raise the schooling of the next generation? *The American Economic Review*, 92(1):324–334.

Bell, M. and Davis, D. (2001). Reassessment of the lethal London fog 1952: novel indicators of acute and chronic consequences of acute exposure to air pollution. *Envrionmental Health Perspective*, 109:389–394.

Black, S., Devereux, P., and Salvanes, K. (2003). Why the apple doesn't fall far: understanding intergenerational transmission of knowledge. Technical Report 10066, NBER Working paper, Cambridge, MA.

Blanchard, O. (1985). Debt, deficits and finite horizon. *Journal of Political Economy*, 93:223–247.

Bloom, D. and Canning, D. (2005). Health and economic growth: Micro and macro evidence. working papers 42, CDDRL, Stanford IIS.

Brunekreef, B. and Holgate, S. T. (2002). Air pollution and health : review. *The Lancet*, 360:1233–1242.

Calvo, G. and Obstfeld, M. (1988). Optimal time-consistent fiscal policy with finite lifetimes. *Econometrica*, 56(2):411–432.

Chay, K. and Greenstone, M. (2003). The impact of air pollution on infant mortality: evidence from geographic variation in pollution shocks induced by a recession. *Quarterly Journal of Economics*, pages 1121–1167.

Chen, S. and Liao, C. (2005). Health risk assessment on humans exposed to environmental polycyclic aromatic hydrocarbons pollution sources. *Science of the Total Environment*.

Chevalier, A. (2004). Parental education and children's education: A natural experiment. Technical Report 1153, IZA Discussion Paper, Institute for the Study of Labor, Bonn, Germany.

Currais, L. and Rivera, B. (1999). Income variation and health: Direct impact or reverse causation. *Applied Economics Letters*, 6:761–764.

Currais, L. and Rivera, B. (2003). The effect of health investment on growth: A causality analysis. *International Advances in Economic Research*, 9(4):312–324.

Daniels, M., Dominici, F., Samet, J., and Zeger, S. (2000). Estimating particulate matter-mortality, dose-response curves and threshold levels: an analysis of daily time series for the 20 largest US cities. *American Journal of Epidemiology*, 152:397–406.

Ding, W., Lehrer, F., Rosenquist, J., and Audrain-McGovern, J. (2005). The impact of health on academic performance: New evidence using genetic markers. Technical report, University of Pennsylvania.

Dominici, F., Daniels, M., Zeger, S., and Samet, J. (2002). Air pollution and mortality: estimating regional and national dose-response relationships. *Journal of the American Statistical Association*, 97(457):100–135.

Dominici, F., Samet, J., and Zeger, S. (2000). Combining evidence on air pollution and daily mortality from the 20 largest US cities: a hierarchical modelling strategy. *Journal of the Royal Statistical Society: series A*, 163(3):263–302.

Dominici, F., Sheppard, L., and Clyde, M. (2003). Health effects of air pollution: a statistical review. *International Statistical Review*, 71:243–276.

Evans, M. F. and Smith, V. (2005). Do new health conditions support mortility-air pollution effects? *Journal of Environmental Economics and Management*, 50:496–518.

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.

Grossman, M. and Kaestner, R. (1997). Effects of education on health. In Behrman, J. and Stacey, N., editors, *The Social Benefits of Education*. University of Michigan Press.

HEI International Scientific Oversight Committee (2004). Health effects of outdoor air pollution in developing countries of Asia: A literature review. Technical report, Special Report 15. Health Effects Institute, Boston, MA.

Koop, G. and Tole, L. (2004). Measuring the health effects of air pollution: To what extent can we really say that people are dying from bad air? *Journal of Environment Economics and Management*, 47(1):30–54.

Kunzli, N., Kaiser, R., Medina, S., Studnicka, M., Chanel, O., Filliger, P., Herry, M., Horak Jr, F., Puybonnieux-Texier, V., Quénel, P., Schneider, J., Seethaler, R., Vergnaud, J., and Sommer, H. (2000). Public-health impact of outdoor and traffic-related air pollution: a European assessment. *The Lancet*, 356:795–801.

Kurttio, P., Pukkala, E., Kahelin, H., Auvinen, A., and Pekkanen, J. (1999). Arsenic concentrations in well water and risk of bladder and kidney cancer in Finland. *Environmental Health Perspectives*, 107(9):705–710.

López-Casanovas, G., Rivera, B., and Currais, L. (2005). *Health and Economic Growth: Findings and Policy Implications*. MIT Press.

Lucas, R. (1988). On the mechanisms of economic development. *Journal of Monetary Economics*, 22:3–42.

Mayer-Foulkes, D. (2005). Human development traps and economic growth. In López-Casanovas, G., Rivera, B., and Currais, L., editors, *Health and Economic Growth: Findings and Policy Implications*. MIT Press.

Morris, R. (1995). Environmental health issues. *Environmental Health Perspectives*, 103(S8).

Nadal, M., Schuhmacher, M., and Domingo, J. (2004). Metal pollution of soils and vegetation in an area with petrochemical industry. *Science of the Total Environment*, 321:59–69.

Oreopoulos, P., Page, M., and Huff Stevens, A. (2003). Does human capital transfer from parent to child? The intergenerational effects of compulsory schooling. Technical Report 10164, NBER Working paper, Cambridge, MA.

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

Paulu, C., Aschengrau, A., and Ozonoff, D. (1999). Tetrachloroethylene-contaminated drinking water in Massachusetts and the risk of colon-rectum, lung, and other cancers. *Environmental Health Perspectives*, 107(4):265–271.

Plug, E. (2004). Estimating the effect of mother's schooling on children's schooling using a sample of adoptees. *The American Economic Review*, 94(1):358–368.

Pope, C., Burnett, R., Thun, M., Calle, E., Krewski, D., Ito, K., and Thurston, G. (2002). Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *The Journal of American Medical Association*, 287:1132–1141.

Schuhmacher, M. and Domingo, J. (2006). Long-term study of environmental levels of dioxins and furans in the vicinity of a municipal solid waste incinerator. *Environment International*, 32:397–404.

Valent, F., Little, D., Bertollini, R., Nemer, L., Barbone, F., and Tamburlini, G. (2004). Burden of disease attributable to selected environmental factors and injury among children and adolescents in Europe. *The Lancet*, 363:2032–2039.

van Ewijk, C. and van Wijnbergen, S. (1995). Can abatement overcome the conflict between environment and economic growth? *De Economist*, 143(2):197–216.

Vellinga, N. (1999). Multiplicative utility and the influence of environmental care on the short-term economic growth rate. *Economic Modelling*, 16(3):307–330.

Vellinga, N. and Withagen, C. (2001). Endogenous growth and environmental policy. *Growth and Change*, 32:92–109.