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# Human capital, pollution control, and endogenous growth

*Birgit Kirschbaum\** and *Susanne Soretz\*\**

January 31, 2017

## Abstract

Human capital and technological change are key factors for the realisation of a sustainable growth path, particularly if production causes environmental pollution. We analyse an endogenous growth model with pollution and abatement. Human capital is used in the production sector as well as in pollution control. In the steady state, economic growth and the level of pollution are constant. We show that greener preferences may increase the pollution level, driven by the decrease in human capital intensity in the production sector and the human capital reallocation.

Technological change is assumed to increase the efficiency of human capital in the abatement process. Hence, pollution control requires less abatement expenditures. Nevertheless, the impact on the steady state pollution level is ambiguous. If the productivity of human capital accumulation is relatively low, the increased efficiency of human capital in pollution control may lead to an increase in pollution. This can help to explain why environmental quality in emerging countries frequently deteriorates.

JEL-Classification: O1, O4, Q2, Q5

Keywords: pollution, endogenous growth, human capital, abatement technology

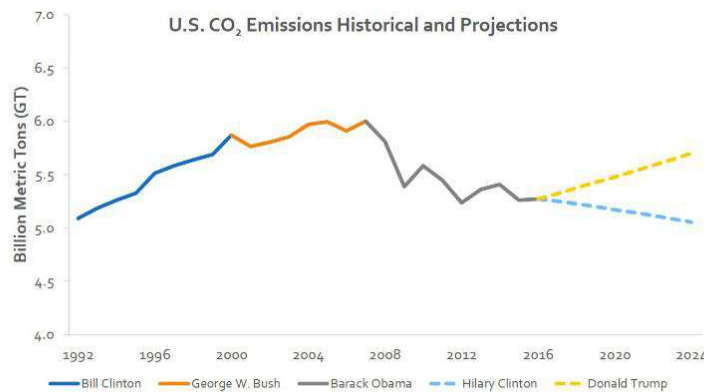
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# 1 Introduction

Pollution is mainly caused by industrial production and therefore increases within the growth process. Nevertheless, this relation is not exogenously given. Pollution can be reduced by abatement activity or technological change. There are economic decisions about the intensity of abatement effort and about the abatement technology. Depending on the decisions on these issues, resulting pollution may rise or fall during the growth process, as illustrated in figure 1.



**Figure 1:** *Development of CO<sub>2</sub>-emissions in the USA, Spiegel online 2016, based on data provided by Lux Research Inc.*  
<http://www.spiegel.de/wissenschaft/natur/bild-1120740-1070775.html>

The German news portal "Spiegel online" published this chart of U.S. CO<sub>2</sub> emissions by the terms of office of the different presidents. First, the policy of Bill Clinton in the 1990s led to a stronger increase in emissions (from approximately 5 billion metric tons to 5.8 billion metric tons) than the years of George W. Bush. When Barack Obama's term of office started, the emissions decreased even about 0.4 billion metric tons in the first year. Under his new administration a clear trend of environmental improvement was observable. The upcoming years will show which effects will result from the new politics of Donald Trump. This example shows that decisions on environmental issues are at least as important for the performance of environmental quality as economic growth rates.

In our model, we focus on the role of human capital, which is used in the production sector as well as in the abatement technology. Human capital accumulation facilitates ongoing growth in the presence of pollution, as already found by Gradus and Smulders

(1993). A lot of models analyse the impact of pollution on human capital accumulation. Pautrel (2009) or Mariani et al. (2010) address the decrease in life expectancy due to pollution, whereas Bretschger and Vinogradova (2017) focus on the uncertainty in human health caused by pollution.

Our focus is different. We emphasise the role of human capital for pollution control. Hence, we analyse the decision on human capital allocation, namely to which extent human capital is assigned to the production sector and to pollution control respectively. Environmental protection is not only due to abatement expenditures, but depends in addition on the quality of abatement activity which is increased by human capital. To give an example, the German federal environmental agency obliged the automotive sector in Germany, to improve pollution control. Induced by political regulations, the automobile industry had to improve catalysts and particle filters. Furthermore, by political sanctions the refineries improved the quality of fuel. Hence technical progress altered the abatement technology and led to a larger importance of human capital compared with abatement expenditures. As a result, pollution emitted by automobiles decreased significantly, this is shown in figure 2.

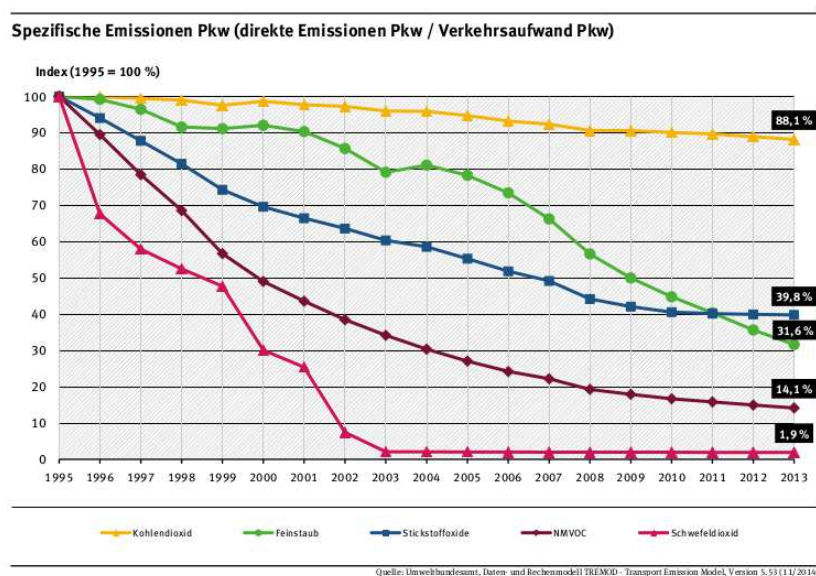


Figure 2: Automobile emissions, Source: <http://www.umweltbundesamt.de/daten/verkehr/schadstoff-treibhausgas-emissionen-des#textpart-1>

We show that the human capital allocation decision crucially influences the steady state growth path. For example, a society with greener preferences will increase abatement ex-

penditures and therefore enlarge production output. The enlargement of the production sector implies a reallocation of human capital in at the expense of abatement activity. The resulting pollution level on the balanced growth path increases.

In addition to human capital accumulation, technological change plays a key role for endogenous growth and as well for sustained growth in spite of environmental pollution. Endogenous technological change is analysed for example by Smulders and de Nooij (2003) who show that costs of energy conservation decrease due to R&D, and that there will be crowding out of non-energy R&D. Manne and Richels (2004) focus on the interdependence between technical change and abatement costs and derive that abatement costs will increase in time. Investment in clean technologies is examined by van der Ploeg and Withagen (1991). This research area observes the effects of technological change on the production process and not, as we do, on the protective measures. Bovenberg and Smulders (1995) extend the framework to a two sector endogenous growth setting and analyse the implications of technological change in the production sector on environmental quality. Grimaud and Tournemaine (2007) as well as Pautrel (2012) work on the growth impact of environmental policy in endogenous growth models with human capital and R&D. Popp et al. (2010) give a comprehensive overview.

In our paper, technological progress is exogenous and increases the importance of human capital in abatement. This setting allows to analyse the impact of a change in abatement technology on economic decisions which in turn influence the pollution level. We show that the impact of technological change in pollution control is ambiguous and depends mainly on the relative productivities of production and human capital accumulation.

The paper is organised as follows: The assumptions of our model are presented in section 2 and the steady state growth path is determined in section 3. Section 4 analyses the impact of an increase in the efficiency of human capital in pollution control and section 5 briefly concludes.

## **2 The model**

We analyse an endogenous growth model with physical and human capital. Production causes pollution and abatement effort can be done to reduce environmental damage. First, we introduce the assumptions of the model and subsequently we will analyse the socially optimal steady state.

The present model consists of a consumption good sector using physical capital and human capital as production factors. The parameter  $A$  denotes the total factor productivity of the production sector and  $\alpha$  is the elasticity of production of physical capital,  $k$ . Accordingly,  $(1 - \alpha)$  denotes the importance of human capital,  $h$ , within the production sector.

$$y = Ak(t)^\alpha (v(t)h(t))^{1-\alpha}, \quad A > 0 \quad (1)$$

Environmental pollution results as a by-product of the use of physical capital in the production sector. For simplicity, we assume the elasticity of pollution with respect to capital to be unity, as can be seen in the numerator of (2). Pollution can be reduced by abatement activity as described in the denominator.

$$P = \frac{k(t)}{e(t)^{(1-\eta)}((1-v(t))h(t))^\eta} \quad (2)$$

Abatement activity consists of abatement expenditures,  $e$ , as part of production output, along with human capital. Consequently human capital,  $h$ , has to be split up between production sector, share  $v$ , and abatement effort, share  $(1 - v)$ . The importance and influence of the environmental protection measures is described by  $\eta$  respectively by  $(1 - \eta)$ . A high  $\eta$  characterises large impact of the use of human capital and specifies human capital intensive pollution control. In this case, abatement technology is quality oriented, e. g. sophisticated air cleaning technologies. In contrast if  $\eta$  is small, abatement expenditures are important for pollution control. Then, abatement technology is rather quantity oriented, e. g. containments for toxic waste.

Physical capital evolves over time as follows:

$$\dot{k}(t) = Ak(t)^\alpha (v(t)h(t))^{1-\alpha} - c(t) - e(t) \quad (3)$$

Thus the growth rate of physical capital depends on the factor intensity, the ratio of consumption to physical capital and on the ratio of abatement expenditures to physical capital.<sup>1</sup>

$$\hat{k} = A \left( \frac{vh}{k} \right)^{1-\alpha} - \frac{c}{k} - \frac{e}{k}$$

Human capital grows with the exogenously given rate  $\hat{h} = B$ . The parameter  $B$  denotes productivity of human capital accumulation.

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<sup>1</sup>For reasons of clarity the dependence to the time can be neglected.

A continuum of infinitely lived households have the same preferences and can be described by a representative household. The representative household maximises his intertemporal utility which is additively separable across time. Future utility is discounted with the constant rate  $\rho > 0$ .

$$U = \exp(-\rho t)u(c, P) \quad (4)$$

The representative household can substitute his consumption intertemporally with the elasticity  $1/\sigma$ . Furthermore the intratemporal elasticity of substitution between consumption and pollution is constant. A closer look at the intratemporal utility function shows that current utility depends on consumption,  $c$ , and environmental pollution,  $P$ . Thereby utility increases with higher consumption and decreases with higher pollution.

$$u(c, P) = \frac{(cP^{-\gamma})^{1-\sigma}}{1-\sigma}, \quad \alpha(1 + \gamma(1 - \eta)) > 1, \quad \sigma > \alpha \quad (5)$$

The negative effect of pollution on utility is driven by the relative impact of dis-utility caused by pollution,  $\gamma$ . This approach already dates back to Forster (1973). He describes pollution as aesthetic cost to the society, reducing their utility and changing their preferences. The individuals gain from less pollution. A higher  $\gamma$  describes a stronger influence of pollution. Then the individuals have more articulate preferences for a clean environment, so called greener preferences. To ensure that a steady state with constant pollution level exists, we will restrict our analyses to parameters which satisfy  $\alpha(1 + \gamma(1 - \eta)) > 1$ . This assumption will be explained with detail after equation (16).

In order to identify the steady state growth path, individual lifetime utility is maximised subject to private capital accumulation according to (3). The Hamiltonian results as

$$\mathbb{H} = \exp(-\rho t) \frac{(cP^{-\gamma})^{1-\sigma}}{1-\sigma} + \lambda(Ak^\alpha(vh)^{1-\alpha} - c - e) \quad (6)$$

The choice variables are consumption,  $c$ , abatement expenditures,  $e$ , and the share of human capital allocated to production of the consumption good,  $v$ . Physical capital,  $k$ , is the state variable.<sup>2</sup> The optimal growth path is determined by the following first order

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<sup>2</sup>In contrast to the archetype model of Lucas (1988), human capital does not appear as a state variable within utility maximisation, since the evolution of human capital in our model is purely exogenous. This simplification is without loss of generality, and the reason is that we focus on the allocation of human capital between production and pollution control, not between production and human capital allocation.

conditions:

$$\frac{\partial \mathbb{H}}{\partial c} = \exp(-\rho t) c^{-\sigma} P^{-\gamma(1-\sigma)} - \lambda \stackrel{!}{=} 0 \quad (7)$$

$$\frac{\partial \mathbb{H}}{\partial e} = \exp(-\rho t) c^{1-\sigma} \gamma P^{-\gamma(1-\sigma)-1} (1-\eta) \frac{P}{e} - \lambda \stackrel{!}{=} 0 \quad (8)$$

$$\frac{\partial \mathbb{H}}{\partial v} = \exp(-\rho t) c^{1-\sigma} \gamma P^{-\gamma(1-\sigma)-1} (-\eta) \frac{P}{1-v} + \lambda A k^{\alpha} h^{1-\alpha} (1-\alpha) v^{-\alpha} \stackrel{!}{=} 0 \quad (9)$$

$$\frac{\partial \mathbb{H}}{\partial k} = \exp(-\rho t) c^{1-\sigma} (-\gamma) P^{-\gamma(1-\sigma)-1} \frac{P}{k} + \lambda A k^{\alpha-1} \alpha (vh)^{1-\alpha} \stackrel{!}{=} -\dot{\lambda} \quad (10)$$

Using (7) and (8) results in

$$\frac{e}{c} = \gamma(1-\eta) \quad (11)$$

and determines the optimal ratio of abatement expenditures,  $e$ , and consumption,  $c$ . Income is used for consumption, abatement expenditures and physical capital accumulation. Of course environmental preferences are an important parameter for the income share of abatement expenditures. The stronger the dis-utility of pollution,  $\gamma$ , the larger is optimal abatement activity and hence the ratio of abatement and consumption.  $1-\eta$  denotes the impact of abatement expenditures on pollution as defined in (2). Mathematically it is (the absolute value of) the elasticity of pollution with respect to abatement expenditures. Hence, one can imagine  $1-\eta$  to be the productivity of produced goods like filters in reducing environmental pollution. The higher the efficiency of abatement expenditures, the higher abatement activity and hence the ratio of abatement and consumption.

Substitution of equation (11) into (9) leads to

$$\frac{e}{k} = (1-\alpha) \frac{(1-\eta)}{\eta} A \left( \frac{vh}{k} \right)^{1-\alpha} \frac{1-v}{v} \quad (12)$$

The optimal ratio of abatement expenditures and physical capital is determined mainly by the relative importance of human capital in pollution control,  $(1-\eta)/\eta$ , average productivity of physical capital in the consumption good sector,  $A(vh/k)^{1-\alpha}$ , and human capital allocation,  $(1-v)/v$ . Abatement expenditures *ceteris paribus* increases, if they get more important in the pollution control technology i. e.  $1-\eta$  rises. And abatement activity increases, if average productivity of physical capital enhances. Then there is more output,  $y$ , from the same amount of capital,  $k$ , so individuals are able to afford a larger amount of abatement expenditures. This can be interpreted as a positive income



effect. Last, abatement activity *ceteris paribus* increases, if human capital is reallocated in favour of pollution control i. e.  $1 - \nu$  rises. If more human capital is used in the abatement process, the marginal pollution decreasing impact of abatement expenditures enlarges. Hence, the incentive for abatement activity increases.

The optimal growth rate of consumption arises by combining equations (7) and (10).

$$\hat{c} = 1/\sigma \left[ \alpha A \left( \frac{vh}{k} \right)^{1-\alpha} - \frac{e}{(1-\eta)k} - \rho - \gamma(1-\sigma)\hat{P} \right] \quad (13)$$

The social marginal return on capital falls short of the private marginal return,  $\alpha A(vh/k)^{1-\alpha}$ , since physical capital causes pollution as a by-product. Hence, the optimal abatement ratio is included and decreases the social marginal productivity of capital. Inserting equation (12) then gives the Keynes-Ramsey-Rule

$$\hat{c} = 1/\sigma \left[ A \left( \frac{vh}{k} \right)^{1-\alpha} \left( \alpha - \frac{1-\alpha}{\eta} \frac{1-\nu}{\nu} \right) - \rho - \gamma(1-\sigma)\hat{P} \right] \quad (14)$$

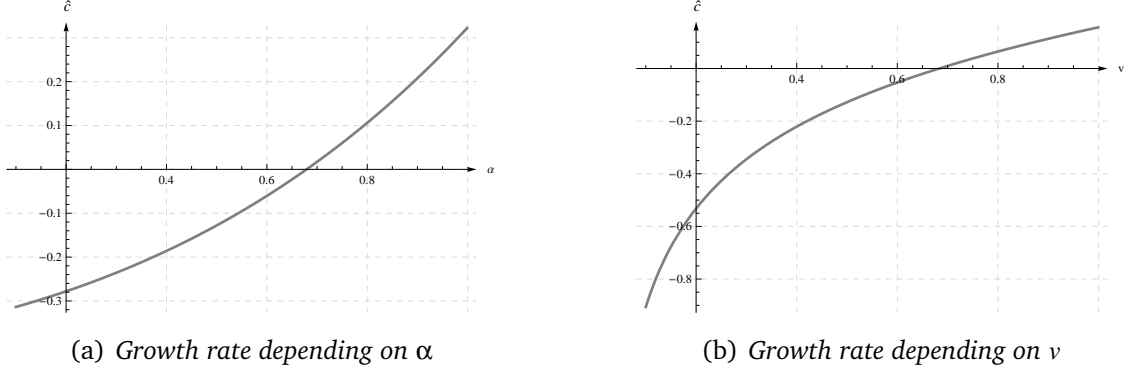
The larger  $\eta$ , the less efficient are abatement expenditures and the more efficient is human capital in pollution control. Hence, the optimal abatement ratio *ceteris paribus* decreases as already shown in equation (12) and consumption growth increases. An increase in the production elasticity of physical capital,  $\alpha$ , increases the direct marginal product of capital, but decreases the productivity of human capital,  $1 - \alpha$ . Therefore human capital is shifted towards abatement activity and there is less need for abatement expenditures to realise the same level of pollution, as can be seen in (12). This is the rationale why optimal consumption growth increases.

### 3 Steady state economic growth and pollution level

We will show that there exists a steady state with constant and equal growth rates of consumption, abatement expenditures, physical and human capital, and constant allocation of human capital. Then the ratio of abatement and physical capital as well as the pollution level remain constant. First, with constant pollution, the growth rate of consumption results in

$$\hat{c} = 1/\sigma \left[ A \left( \frac{vh}{k} \right)^{1-\alpha} \left( \alpha - \frac{1-\alpha}{\eta} \frac{1-\nu}{\nu} \right) - \rho \right] \quad (15)$$

and it is straightforward that consumption growth will be constant if physical and human capital grow at a common rate and human capital allocation does not change. Furthermore, it can be seen that positive growth will only be feasible if the production elasticity of physical capital is sufficiently high (see figure 3(a)) and if the share of human capital used in production is sufficiently large (see figure 3(b)).



**Figure 3:** Consumption growth rate,  $\hat{c}$ ;  
parameters:  $\alpha = 0.5, \eta = 0.5, \rho = 0.03, \sigma = 3, h = 1, k = 1, A = 1$

It will be shown later, that  $\eta$  is the exogenous parameter determining the human capital allocation, and that the share of human capital used in production will be high if the efficiency of human capital in pollution control,  $\eta$ , is small. Hence, if the production elasticity of physical capital is too small or the impact of abatement expenditure on the pollution level is not large enough, a steady state with constant pollution is not feasible. Abatement expenditures would have to be very large or physical would have to be very small to ensure the pollution level to remain constant. This would not be consistent with positive consumption growth. We will exclude these parameter settings in our further analysis, because they are not compatible with inner solutions of utility maximisation.

In the steady state consumption and physical capital will grow with the exogenously given growth rate of human capital,  $\hat{c} = \hat{k} = B$ . Equalising the growth rate of consumption with  $B$  gives the capital ratio  $vh/k$  and subsequently the abatement ratio  $e/k$ . Utilising both terms in  $\hat{k} = B$  results in optimal human capital allocation,  $(1 - v)/v$ . The closed form solution can be described by abatement ratio, capital ratio and human capital allocation which together determine the pollution level.

The steady state ratio of abatement expenditures and physical capital is

$$\left(\frac{e}{k}\right)^* = \frac{(1 - \eta)(B(\sigma - \alpha) + \rho)}{\alpha(1 + \gamma(1 - \eta)) - 1} \quad (16)$$

Easily can be seen that the abatement ratio will only be positive if  $\alpha$  and  $1 - \eta$  are sufficiently high, as already mentioned above. Additionally, environmental preferences,  $\gamma$  have to be sufficiently strong, otherwise individuals would not choose a steady state with constant pollution level. Rigorously speaking,  $\alpha(1 + \gamma(1 - \eta)) > 1$  must be satisfied as assumed in equation (5). Physical capital has to be sufficiently productive and abatement expenditure has to be sufficiently efficient in reducing pollution. Otherwise, a steady state with constant pollution level would not be feasible.

An increasing productivity of human capital accumulation,  $B$ , will unambiguously increase the abatement ratio due to a positive income effect. Income grows faster if  $B$  is higher. Hence, individuals can increase consumption as well as abatement expenditures and benefit from a reduced level of pollution.

In steady state the ratio of human to physical capital in the production sector is given by

$$\left(\frac{vh}{k}\right)^{1-\alpha*} = \frac{\sigma B + \rho}{A \left( \alpha - \frac{B(\sigma - \alpha) + \rho}{(\sigma B + \rho)(1 + \gamma(1 - \eta)) - B} \right)} \quad (17)$$

and human capital allocation is described with

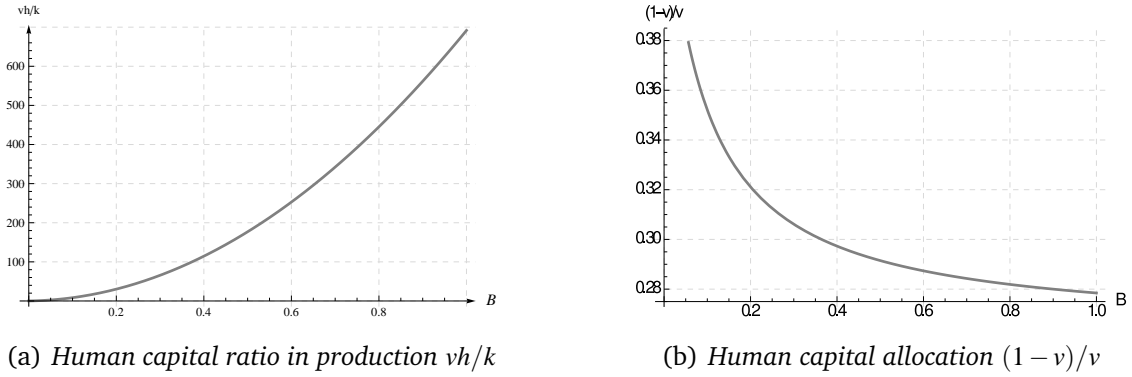
$$\left(\frac{1-v}{v}\right)^* = \frac{\eta}{1-\alpha} \frac{B(\sigma - \alpha) + \rho}{(\sigma B + \rho)(1 + \gamma(1 - \eta)) - B} \quad (18)$$

An increase in the total factor productivity  $A$  of the consumption goods sector will increase physical capital accumulation and thereby reduce the ratio of human to physical capital in production. The impact of a rise in the productivity of human capital accumulation,  $B$ , is displayed in figure 4. For all feasible parameter settings, it increases the human capital ratio, because human capital becomes relatively less scarce. Thereby it increases physical capital productivity and reinforces the incentive to accumulate capital. Hence, with increased physical capital accumulation, there is also more need for human capital in production, and the share of human capital designated to control pollution,  $1 - v$ , decreases.

Steady state pollution results from economic decisions on capital accumulation, human capital allocation and abatement activity.

$$P = \frac{k}{e^{(1-\eta)((1-v)h)^\eta}} = \left(\frac{e}{k}\right)^{-(1-\eta)} \left(\frac{vh}{k}\right)^{-\eta} \left(\frac{1-v}{v}\right)^{-\eta} \quad (19)$$

Obviously, pollution decreases in the abatement ratio,  $e/k$ . The second term shows that pollution decreases if human capital intensity in production,  $vh/k$ , increases. This is a



**Figure 4:** Impact of an increase in human capital growth,  $B$ ;  
parameters:  $\alpha = 0.5, \gamma = 3, \eta = 0.5, \rho = 0.03, \sigma = 3, A = 1,$

direct consequence from the assumption that only physical capital in production causes pollution. And the last term demonstrates the impact of human capital allocation. An increase in  $v$  extends production and decreases the part of human capital used to control pollution. Ceteris paribus, the pollution level increases.

Using the steady state relations given in equation (16), (17) and (18) the pollution on the balanced growth path can be represented as

$$P^* = \left( \frac{(1-\eta)(B(\sigma-\alpha)+\rho)}{\alpha(1+\gamma(1-\eta))-1} \right)^{-(1-\eta)} \left( \frac{\sigma B + \rho}{A \left( \alpha - \frac{B(\sigma-\alpha)+\rho}{(\sigma B + \rho)(1+\gamma(1-\eta))-B} \right)} \right)^{-\frac{\eta}{1-\alpha}} \cdot \left( \frac{\eta}{1-\alpha} \frac{B(\sigma-\alpha)+\rho}{(\sigma B + \rho)(1+\gamma(1-\eta))-B} \right)^{-\eta} \quad (20)$$

As easily can be seen, the pollution level indeed remains constant on the steady state growth path. Nevertheless, the adaption caused by changes in the general framework are complex. In the next section, we will analyse the consequences of greener preferences as well as the impacts of technological change.

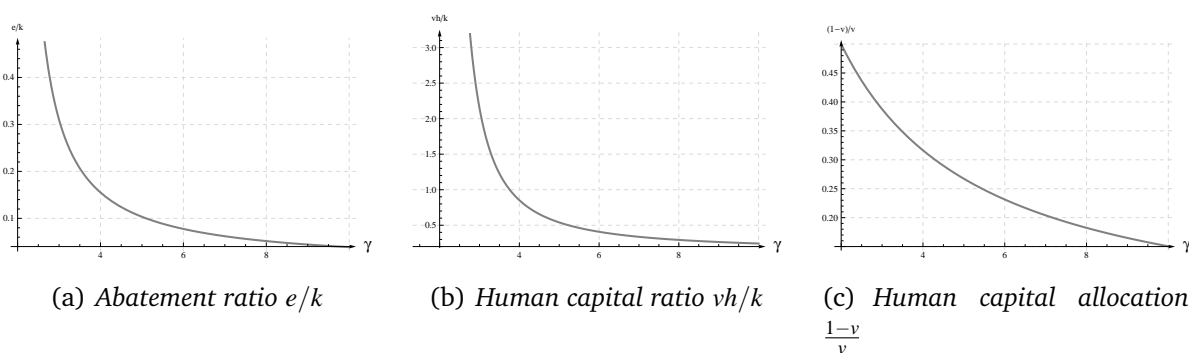
## 4 Greener preferences, technological change and steady state pollution

The importance of pollution for individual utility is denoted by the parameter  $\gamma$  (see the utility function (5)). Hence if individuals suffer more from environmental pollution or if

the preferences of the society change and environmental quality is taken more seriously, this is reflected in our model by an increase in  $\gamma$ .

Steady state growth is predetermined by the growth rate of human capital. Since only physical capital and not human capital is a source of environmental pollution, greener preferences do not affect the steady state growth rate. The production structure is adjusted such that the social marginal rate of return enables the realisation of the unchanged rate of growth  $\hat{c} = \hat{h} = B$ . This is a well known feature of endogenous growth models with pollution and human capital and was already discussed in Gradus and Smulders (1993). Nevertheless, consumption and abatement decisions, capital accumulation and human capital allocation will change.

With greener preferences, of course there is an incentive to reduce pollution by increased effort in abatement activity or by reduced physical capital use. But there is also an incentive to substitute away from environmental quality and to maintain the welfare level by an increase in future consumption which implies an increase in physical capital accumulation.<sup>3</sup> From the equations (16), (17) and (18) it is straightforward that an increase in  $\gamma$  immediately decreases abatement expenditures, human capital intensity in production and the share of human capital devoted to pollution control. Additionally we give these adjustments in figure 5.



**Figure 5:** Impact of greener preferences,  $\gamma$ ;  
parameters:  $\alpha = 0.5, \eta = 0.5, \rho = 0.03, \sigma = 3, A = 1, B = 0.05$

In a society with greener preferences, abatement expenditures,  $e$ , are increased in order

<sup>3</sup>The potentially pollution-increasing effect of greener preferences is also explained in Smulders and Gradus (1996), but for a model without human capital. Without human capital,  $1 - \eta < 1$  and even  $\eta = 0$  would imply that greener preferences would cause decreasing pollution.

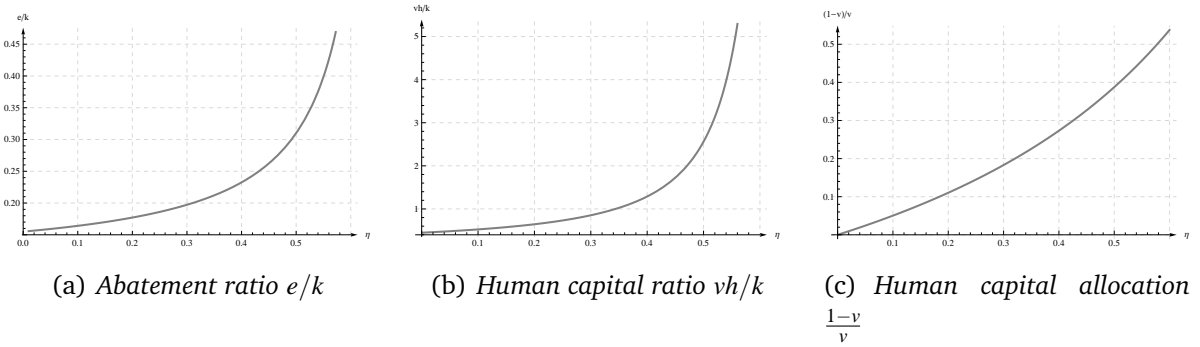
to reduce the pollution level. In order to provide more abatement expenditures, production has to be expanded. Therefore, the level of physical capital must be increased. The abatement ratio decreases because physical capital increases faster than abatement expenditures. The reason is that human capital accumulation is exogenous and cannot be accelerated. Hence, additional production is only possible by increasing the physical capital input and by reallocating human capital. In direct consequence, the pollution level increases. Nevertheless, the utility decline is in part compensated by an increase in future consumption.

In the following, we analyse the impact of technological change, and we focus on an increase in the efficiency of human capital in pollution control. Within the last decades, there was great effort to increase the efficiency of pollution abatement. And there was a sustained increase in the importance of human capital in pollution abatement. Hence, abatement technology got increasingly human capital intensive. In our model, this change is represented by a rise in the parameter  $\eta$ .

The augmenting relevance of human capital in pollution abatement delivers complex effects on the level of pollution. First, there is a direct impact on pollution which is captured by the exponents in equation (19). A change in the abatement technology which increases  $\eta$ , decreases the relative importance of abatement expenditures,  $e$ , and increases the importance of human capital devoted to pollution control,  $(1 - \nu)h$ . The pollution level is influenced ambiguously. The increase in the relative importance of human capital decreases pollution, but the reduced relative importance of abatement expenditures increases pollution. Moreover, there are indirect effects of the increase in  $\eta$  on pollution which are due to the adjustment of the economic decisions on abatement expenditures, capital accumulation and human capital allocation.

Starting with the effect of increasing  $\eta$  on the ratio of environmental abatement expenditures and physical capital  $e/k$  (as given in equation 16), there is a positive impact as displayed in figure 6(a). With an increase in  $\eta$ , relative efficiency of abatement expenditures,  $1 - \eta$ , decreases. Therefore, abatement expenditures have to be increased in order to compensate at least partly for the loss in efficiency. The ratio of abatement expenditures to physical capital increases unambiguously.

The effect of increasing  $\eta$  on the optimal ratio between physical capital and human capital in the production sector is negative and shown in figure 6(b). As the efficiency of human capital in pollution control,  $\eta$ , increases, the overall importance of human capital for the economy increases. Therefore, the optimal human capital intensity in the



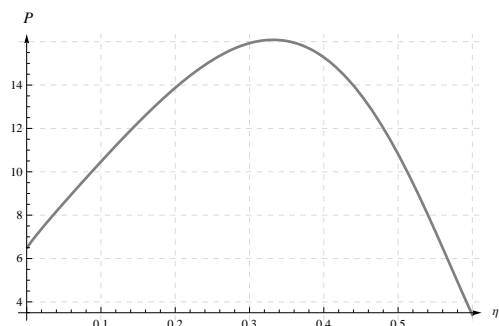
**Figure 6:** *Impact of technological change,  $\eta$ ;*  
*parameters:  $\alpha = 0.5, \gamma = 3, \rho = 0.03, \sigma = 3, A = 1, B = 0.05$*

economy increases and  $vh/k$  rises. With this respect, an increase in  $\eta$  can be interpreted as a switch to a less quantitative but more qualitative environmental improvement. As a response, the economy develops towards a less physical capital intensive production and *ceteris paribus* a smaller pollution level.

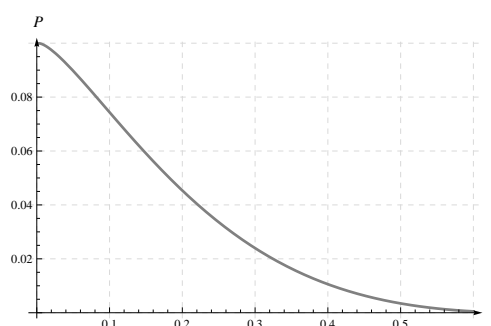
The third effect of an increase in the efficiency of human capital in pollution control,  $\eta$ , concerns the allocation of human capital. The impact of  $\eta$  on the share of human capital devoted to environmental conservation,  $1 - v$ , is positive. Consequently, the share of human capital used in production,  $v$ , decreases. The impact on the third term  $(1 - v)/v$  in pollution (19) is given in figure 6(c). This reflects a simple substitution process. As the importance of human capital for the pollution level increases, the allocation of human capital changes in favour of pollution control and pollution *ceteris paribus* will fall.

To summarise, all three effects discussed so far lead to reduced pollution. Increased abatement expenditures, decreased physical capital intensity and reallocation of human capital in favour of pollution control likewise foster environmental conservation. Nevertheless, the pollution level also may increase as a consequence of enhanced efficiency of human capital in pollution control due to the direct impact of  $\eta$  on pollution already described above. An increase in  $\eta$  can either decrease or increase the pollution level as shown in figures 7(a) and 7(b).

The overall impact of  $\eta$  on pollution mainly depends on the productivity of the production sector,  $A$ , and the productivity of human capital accumulation,  $B$ . If the productivity of human capital accumulation,  $B$ , is relatively low, the economy mainly relies on consumption/investment good production. Environmental conservation is predominantly induced by abatement expenditures,  $e$ . Hence, a rise in  $\eta$  which reduces efficiency of



(a) Relatively high productivity B:  $A = 1, B = 4$



(b) Relatively high productivity A:  $A = 6, B = 0.05$

**Figure 7:** Pollution level and efficiency,  $\eta$ ; parameters:  $\alpha = 0.5, \gamma = 3, \rho = 0.03, \sigma = 3$

abatement expenditures and enhances efficiency of human capital in pollution control, may increase the pollution level, see figure 7(b). This will happen whenever the pollution increasing effect of the declined efficiency of abatement expenditures overcompensates the pollution decreasing effect induced by the adjustment of economic decisions on abatement, physical capital intensity and human capital allocation described above.

If instead the productivity of human capital accumulation is relatively high, the economy is mainly human capital oriented. And human capital plays an important role in environmental conservation. Therefore, pollution decreases unambiguously, see figure 7(a). The direct impact of the increase in the efficiency of human capital dominates the impact of decreased efficiency of abatement expenditures, hence the pollution level is reduced.

To conclude, technological progress which leads to higher efficiency of human capital in pollution control enables a shift towards more qualitatively driven environmental conservation instead of merely quantitative measures. Hence, there can be used more intelligent abatement strategies requiring higher levels of human capital in pollution control. Abatement expenditures like quantities of filter systems consequently can be reduced. Nevertheless, only if the productivity of human capital accumulation is sufficiently high, this kind of technological progress indeed will reduce the resulting pollution level in the economy. Only with a sufficiently productive human capital accumulation sector, the ecological system of the economy will benefit from this type of technological progress in pollution control. Hence, we can help to explain why in a wide range of emerging economies the increase in the efficiency of human capital in pollution control does not result in enhanced environmental protection.



## 5 Conclusion

We analysed an endogenous growth model with human and physical capital. Physical capital causes environmental pollution which can be reduced through an abatement technology. Abatement expenditures together with human capital are necessary to control pollution. An increase in the share of human capital which is assigned to pollution control corresponds to more qualitatively oriented pollution control, e. g. intelligent filter systems, whereas an increase in abatement expenditures corresponds to more quantitatively oriented pollution control, e. g. more filters.

There exists a steady state growth path with constant and equal growth rates of consumption, abatement expenditures, physical and human capital. The level of pollution, allocation of human capital and physical capital intensity in production remain constant in the steady state.

We show that a society with greener preferences accepts a higher steady state pollution level. Abatement expenditures are increases, but since human capital accumulation cannot be accelerated, more physical capital is used in the production sector. Moreover, human capital is reallocated in favour of production, such that the share of human capital assigned to abatement decreases. Hence, the pollution level increases, but the negative welfare implications can partly be compensated by increased future consumption.

Technological change is specified to increase the efficiency of human capital in the abatement technology. We have in mind that technological change enables better techniques for pollution control. Consequently, the allocation of human capital is adjusted and the share of human capital which is used in pollution control increases. The ratio of abatement expenditures to physical capital increases too, because the incentive to engage in abatement increases due to technological progress. And third, the ratio of physical to human capital in production is decreased, since the technological change makes human capital more productive, hence capital accumulation gets relatively less attractive. All three economic adjustments *ceteris paribus* decrease pollution.

However, abatement expenditures get less important through this type of technological change. Hence, pollution may decrease if abatement expenditures are sufficiently important within abatement technology in the considered economy. This case will apply, if the productivity of human capital accumulation is relatively low compared with the productivity of the production sector. Typically this might occur for emerging economies.

## Appendix: Derivation of parameter restrictions

The steady state with constant pollution level is induced by  $\alpha(1 + \gamma(1 - \eta)) > 1$ . The following paragraph shows the derivation of this sufficient condition.

$$A \left( \frac{vh}{k} \right)^{1-\alpha} \underbrace{\left( \alpha - \frac{1-\alpha}{\eta} \frac{1-v}{v} \right)}_{\stackrel{!}{>0}} = \sigma B + \rho \quad (21)$$

The social marginal rate of return needs to be positive and leads to a positive denominator of equation (17), as will be deduced in the following.

$$\frac{1-v}{v} \stackrel{!}{<} \alpha \frac{\eta}{1-\alpha} \quad (22)$$

Using equation (18) results in

$$\frac{B(\sigma - \alpha) + \rho}{(\sigma B + \rho)(1 + \gamma(1 - \eta)) - B} \stackrel{!}{<} \alpha \quad (23)$$

But for a positive abatement ratio it must apply:  $\alpha(1 + \gamma(1 - \eta)) > 1$

$$\alpha(1 + \gamma(1 - \eta))B > B \quad (24)$$

$$(\sigma B + \rho)(1 + \gamma(1 - \eta)) - \alpha(1 + \gamma(1 - \eta))B < (\sigma B + \rho)(1 + \gamma(1 - \eta)) - B \quad (25)$$

$$(1 + \gamma(1 - \eta))(\sigma B + \rho - \alpha B) < (\sigma B + \rho)(1 + \gamma(1 - \eta)) - B \quad (26)$$

$$\frac{\sigma B + \rho - \alpha B}{(1 + \gamma(1 - \eta))(\sigma B + \rho - \alpha B)} > \frac{\sigma B + \rho - \alpha B}{(\sigma B + \rho)(1 + \gamma(1 - \eta)) - B} \quad (27)$$

$$\frac{1}{1 + \gamma(1 - \eta)} > \frac{B(\sigma - \alpha) + \rho}{(\sigma B + \rho)(1 + \gamma(1 - \eta)) - B} \quad (28)$$

$$\Rightarrow \alpha > \frac{1}{1 + \gamma(1 - \eta)} > \frac{B(\sigma - \alpha) + \rho}{(\sigma B + \rho)(1 + \gamma(1 - \eta)) - B} \quad (29)$$

This equation is true, if  $\alpha(1 + \gamma(1 - \eta)) > 1$  and thus  $\alpha > \frac{1-\alpha}{\eta} \frac{1-v}{v}$  and the denominator needs to be positive.

$$(\sigma B + \rho)(1 + \gamma(1 - \eta)) - B > 0 \quad (30)$$

with  $(1 + \gamma(1 - \eta)) > 1/\alpha$

$$(\sigma B + \rho)(1 + \gamma(1 - \eta)) - B > 0 \quad (31)$$

$$(\sigma B + \rho)(1 + \gamma(1 - \eta)) - B > 0 \quad (32)$$

$$\sigma B + \rho - \alpha B > 0 \quad (33)$$

So that  $\alpha(1 + \gamma(1 - \eta)) > 1$  is a sufficient condition for the denominator of (17) to be positive.

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