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. The impact of technological change on the pollution level is shown to depend on the development stage of the economy. Less developed economies with a lower productivity level in the education sector benefit more from productivity improvements in the education sector which reduce the pollution level as a by-product. In contrast, more developed economies with a higher productivity level in the education sector experience stronger environmental improvements from technological change in the abatement sector. Higher quality in abatement activity allows for a decrease of abatement expenditures associated with a decreased pollution level.
1 Introduction

With pollution mainly caused by industrial production and increasing within the growth process, there is a natural trade-off between development and environmental care. A lot of approaches around the Environmental Kuznets Curve analyse the impact of income growth on environmental quality. Nevertheless, this relation is not exogenously given. Pollution can be reduced by abatement activity or technological change. Our model points out the impact of technological progress on abatement technology and thereby on the pollution level. We distinguish technological progress in production, in human capital accumulation and in the abatement sector. The impact of technological change on environmental quality is shown to be ambiguous and to depend on the source of technological progress as well as on the level of economic development in the considered economy.

We find that relatively less developed countries, which are characterised by a low level of human capital growth, should focus on the enhancement of the education sector to reduce environmental pollution. In contrast, technological progress in the abatement reducing effect of human capital will enhance environmental quality predominantly in more developed countries, which are characterised by high levels of human capital growth.

Selden and Song (1994), Grossman and Krueger (1995) and Hettige et al. (1992) are early precursors who analysed the correlation between the urban air pollution and GDP. Selden and Song (1994) conclude that technological progress reduces the pollution level only in the early development stages. But air pollution is only one form of environmental pollution, which influences the everyday life of people. It affects vital products like food or it reduces people's ability to work. Hence the need of environmental protection like emissions' reduction and the improvement of the existing measures is constantly rising. A well known approach concerns the technological progress for the improvement of abatement activities. That is why 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, as given in figure 1.

![Automobile emissions](http://www.umweltbundesamt.de/daten/verkehr/schadstoff-treibhausgas-emissionen-des#textpart-1)

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

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 (1997) extend the framework to a two sector endogenous growth setting.

In our paper, technological progress is exogenous and increases either the importance of human capital in abatement or the productivity of human capital accumulation. 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. Groot et al. (2004) explained the existence of a Kuznets Curve for China. They also bring up that the development of China was correlated with increasing environmental problems. That is only one example which raises the question of whether the development process and environmental protection are contradictory.

Our paper is organised as follows: The assumptions of our model are presented in section 2 and the market equilibrium is determined in section 3. Section 4 analyses steady state growth and pollution as well as the relevance of the perceived individual impact on pollution. Section 5 explains the impact of an increase in the efficiency of human capital in pollution control and section 6 briefly concludes.

2 The model

We analyse an endogenous growth model with physical and human capital. Production causes pollution as a by-product of the production process and abatement effort can be done to reduce environmental damage, by spending a fraction of the consumption good for environmental care. Additionally, pollution can be reduced by human capital devoted to abatement activity, hence human capital has to be distributed between the production and the abatement sector.

The consumption good sector uses 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. Production technology
is given by
\[ y = Ak(t)^{\alpha}(v(t)h(t))^{1-\alpha}, \quad A > 0, \quad 0 < \alpha < 1 \quad (1) \]

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
\[ P = \frac{k(t)}{e(t)^{(1-\eta)}((1-v(t))h(t))^{\eta}}, \quad 0 < \eta < 1 \quad (2) \]

Pollution can be reduced by abatement activity as described in the denominator. Abatement activity consists of abatement expenditures, \( e \), as part of production output, along with human capital, \( h \). Consequently, human capital 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 \( \eta \) (and \( (1-\eta) \) respectively). A high \( \eta \) characterises a 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\(^1\)
\[ \dot{k} = A \left( \frac{vh}{k} \right)^{1-\alpha} - \frac{c}{k} - \frac{e}{k} \quad (4) \]

Human capital grows with the exogenously given rate \( \dot{h} = B \). The parameter \( B \) denotes productivity of human capital accumulation and reflects mainly the performance of the education sector.

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
\[ U = \int_{0}^{\infty} \exp(-\rho t)u(c, \bar{P}) dt, \quad \rho > 0 \quad (5) \]

\(^1\)For reasons of clarity the dependence to the time can be neglected.
Future utility is discounted with the constant rate $\rho$. Current utility depends on consumption, $c$, and environmental pollution. 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. Thereby utility increases with higher consumption and decreases with higher pollution as given by

$$u(c, \bar{P}) = \frac{(c\bar{P} - \gamma)^{1-\sigma}}{1-\sigma}, \quad \gamma, \sigma > 0, \quad \alpha(1 + \gamma \delta(1 - \eta)) > \gamma \delta, \quad \sigma > \alpha \quad (6)$$

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 $\alpha(1 + \gamma \delta(1 - \eta)) > \gamma \delta$.

This assumption will be explained with detail after equation (19).

Pollution is a public good, hence non-excludability applies. The straightforward consequence in this context is that individuals neglect the impact of their individual decisions on the aggregate pollution level. However, in reality there is some kind of individual responsibility towards environmental concerns: households separate their waste, they eat vegetarian food or they cut down their energy consumption for environmental reasons.\(^2\) We take this behaviour into account and assume that individuals are aware of some part of individual impact on the pollution level. Within individual utility maximisation pollution is perceived to depend in part, $\delta$, on individual decisions and in part, $1 - \delta$, on aggregate behaviour\(^3\) according to

$$\bar{P} = \delta k \frac{e^{(1-\eta)((1-\nu)h)\eta}}{E^{(1-\eta)((1-\nu)H)\eta}} + (1 - \delta) K \frac{k}{E^{(1-\eta)((1-\nu)H)\eta}} \quad 0 < \delta \leq 1 \quad (7)$$

This assumption describes the environmental responsibility of the households. A higher perception parameter $\delta$ of the individual impact on pollution implies more ambitious environmental care. $\delta = 1$ indicates the special case that individuals feel completely responsible for environmental quality and the market equilibrium coincides with the social optimum. For $\delta = 0$ the individuals neglect their individual impact on the pollution level entirely and completely free-ride.

\(^2\)See for example European Commission (2014, question QA11).

\(^3\)The aggregate variables are denoted with capital letters and exogenous to individual decisions.
3 The market equilibrium

In the dynamic market equilibrium, individuals maximise their lifetime utility subject to private capital accumulation according to (3). The Hamiltonian results in

\[ H = \exp\left( -\rho t \right) \frac{(c \bar{P}^{-\gamma})^{1-\sigma}}{1-\sigma} + \lambda (Ak^\alpha (vh)^{1-\alpha} - c - e) \]  

(8)

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.\(^4\) The optimal growth path is determined by the following first order conditions:

\[ \frac{\partial H}{\partial c} = \exp(-\rho t)c^{-\sigma}\bar{P}^{-\gamma(1-\sigma)} - \lambda \overset{!}= 0 \]  

(9)

\[ \frac{\partial H}{\partial e} = \exp(-\rho t)c^{1-\sigma}\bar{P}^{-\gamma} \delta(1-\eta) \frac{\bar{P}}{e} \overset{!}= 0 \]  

(10)

\[ \frac{\partial H}{\partial v} = \exp(-\rho t)c^{1-\sigma}(\gamma \bar{P}^{-\gamma(1-\sigma)} - 1) \delta(-\eta) \frac{\bar{P}}{1-v} + \lambda A k^\alpha (vh)^{1-\alpha} \overset{!}= 0 \]  

(11)

\[ \frac{\partial H}{\partial k} = \exp(-\rho t)c^{1-\sigma}(-\gamma) \bar{P}^{-\gamma(1-\sigma)} \delta \frac{\bar{P}}{k} + \lambda A k^\alpha - 1 \alpha (vh)^{1-\alpha} \overset{!}= -\dot{\lambda} \]  

(12)

Using (9) and (10) results in

\[ \frac{e}{c} = \gamma \delta (1-\eta) \]  

(13)

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 as well as pollution perception are important parameters for the income share of abatement expenditures. The stronger the dis-utility of pollution (rising \( \gamma \)) or the more households feel individually responsible for the pollution level (increasing \( \delta \)), 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 understand \( 1 - \eta \) to be the productivity of produced goods like filters in reducing environmental pollution.

\(^4\)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.
The higher the efficiency of abatement expenditures, the higher abatement activity and hence the ratio of abatement and consumption.

Substitution of equation (13) into (11) leads to

\[
\frac{e}{(1-v)h} = (1-\alpha) \frac{1-\eta}{\eta} A \left( \frac{k}{vh} \right)^{\alpha}
\]  

(14)

The optimal ratio of abatement expenditures and human capital dedicated to abatement — quantity and quality of abatement activity — is determined mainly by the relative importance of human capital in pollution control, \((1-\eta)/\eta\), and average productivity of physical capital in the consumption good sector, \(A(vh/k)^{1-\alpha}\). This can be interpreted as a kind of arbitrage condition for the efficient combination of \(e\) and \(h\) the abatement process. Abatement expenditures, \(e\), ceteris paribus increase, if they get more important in the pollution control technology i.e. \(1-\eta\) rises. And abatement expenditures increase the relative to human capital, 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.

Equation (14) additionally shows that partial perception of the individual impact on pollution, \(\delta < 1\), does not influence the individually optimal abatement ratio. As already discussed with equation (13), the negative environmental externality decreases abatement expenditures relative to individual consumption. Nevertheless, the negative externality affects abatement expenditures and abatement human capital to the same extend, hence the individually chosen ratio (14) does not display the distortion.

Combining equations (9) and (12) yields the equilibrium growth rate of consumption

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

(15)

Abatement expenditures reduce the marginal return on capital in the production sector, \(\alpha A(vh/k)^{1-\alpha}\), since physical capital causes pollution as a by-product and therefore implies a need for environmental care. Inserting equation (14) then gives the Keynes-Ramsey-Rule

\[
\hat{c} = \frac{1}{\sigma} \left[ A \left( \frac{vh}{k} \right)^{1-\alpha} \left( \alpha - \frac{1-\alpha}{\eta} \frac{1-v}{v} \right) - \rho - \gamma(1-\sigma)\hat{\theta} \right]
\]  

(16)

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 (14) 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 (14). Spending more human capital in environmental protection leads to a higher intensity of physical capital in the production sector. The abatement expenditures are compensated with human capital. So these abatement expenditures are not necessary anymore for environmental care, they are available for consumption. This is the rationale why optimal consumption growth increases.

4 Steady state 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

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

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 2(a)) and if the share of human capital used in production is sufficiently large (see figure 2(b)).

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, $\alpha$, is too small or the impact of abatement expenditure on the pollution level, $(1 - \eta)$, is not large enough, a steady state with constant pollution is not feasible. Abatement expenditures would have to be very large or physical capital 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,
considering $\alpha$ and $(1 - \eta)$, 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, $\dot{c} = \dot{k} = B$. Equalising the growth rate of consumption with $B$ gives the capital ratio $\frac{\dot{c}}{\dot{k}} = B$. Utilising both terms in $\dot{k} = B$ 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

$$P = \frac{k}{e^{(1-\eta)/(1-v)\eta}} = \left(\frac{e}{k}\right)^{(1-\eta)} \left(\frac{v h}{k}\right)^{-\eta} \left(\frac{1 - v}{v}\right)^{-\eta}$$  \hspace{1cm} \text{(18)}

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

The steady state ratio of abatement expenditures and physical capital is

$$\left(\frac{e}{k}\right)^* = \frac{\gamma \delta (1 - \eta)(B(\sigma - \alpha) + \rho)}{\alpha(1 + \gamma \delta (1 - \eta)) - \gamma \delta}$$  \hspace{1cm} \text{(19)}
Easily can be seen that the abatement ratio will only be positive if $\alpha$ and $1 - \eta$ are sufficiently high, as already mentioned above. Physical capital has to be sufficiently productive and abatement expenditure has to be sufficiently potent in reducing pollution. Otherwise, a steady state with constant pollution level would not be feasible. Additionally, the perceived negative impact of pollution on utility, $\gamma \delta$, has to be sufficiently low, otherwise individuals would not choose a positive steady state growth rate. More precisely, $\alpha (1 + \gamma \delta (1 - \eta)) > \gamma \delta$ must be satisfied as assumed in equation (6).

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

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

and human capital allocation is described with

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

An increase in the total factor productivity $A$ of the consumption goods sector will increase physical capital accumulation and thereby unambiguously reduce the ratio of human to physical capital in production. The impact of an increase in the productivity $B$ of human capital accumulation nevertheless is more complex and will be analysed in section 5.

Using the steady state relations given in equation (19), (20) and (21) the pollution on the balanced growth path can be represented as

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

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 following we demonstrate the consequences of greener preferences or a change in environmental responsibility on the pollution level. The impacts of technological change will be analysed in the next section.

The importance of the environment for individual utility is denoted by the parameter $\gamma$ (see the utility function (6)). Hence if individuals suffer more from environmental degradation 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 $\gamma$. However, individual decisions are only affected by environmental preferences to the extent of perceived individual responsibility for the environment, $\delta$ (see pollution perception (7)). Therefore the pollution level is influenced only through the joint channel of perceived individual impact on the environment, $\gamma \delta$.

With an increase in the perceived individual impact on pollution, of course there is an incentive to reduce pollution by increased effort in abatement activity, by reduced physical capital use or by a shift of human capital towards abatement activity. We give these adjustments in figure 3.

![Graphs showing the impact of perceived pollution](figure3)

**Figure 3:** Impact of perceived pollution, $\gamma \delta$;
parameters: $\alpha = 0.7, \eta = 0.5, \rho = 0.03, \sigma = 3, A = 1, B = 0.05$

A rise in $\gamma \delta$ immediately increases abatement expenditures, human capital intensity in production and the share of human capital devoted to pollution control. As observable in figure 3 all three ratios increase with a higher perceived impact on pollution. The production side substitutes physical capital by human capital, such that the amount of human capital used in the production sector decreases. Hence a higher amount of human capital can be invested in abatement activities. In direct consequence, the pollution level decreases, as illustrated in figure 4.

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, the perceived impact on environmental protection does 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).

5 Technological change, development and steady state pollution

Within the last decades, there was great effort to increase the efficiency of pollution abatement. At the same time, the development process is mainly driven by the incentive to increase the income of a country. We present the interdependencies of different development strategies and the respective effects on the pollution level. An increase in productivity will lead to environmental degradation or improvement, depending on whether it occurs in the production sector or in the education sector. And the impact of technical change in the abatement sector on environmental quality will be shown to depend on the productivity level of human capital accumulation.

First we focus on the technological progress, which is well known to go along with economic development. However, the impact of technological progress on environmental quality depends on whether it occurs in the production sector (increasing $A$), or in the education sector (increasing $B$). Figure 5 shows that a productivity increase leads to opposing trends in the pollution level.
An increase in the total factor productivity $A$ increases the production of the homogeneous consumption and investment good. Consequently physical capital accumulation increases. Although the steady state growth rate of physical capital remains unchanged, the overall ratio of physical to human capital, $k/h$, increases. Nevertheless, human capital allocation is not affected as can be seen in equation (21). Hence the decrease in the human capital intensity in production discussed with equation (20) is directly driven by the rise in physical capital endowment due to the increase in $A$. The pollution level increases, as demonstrated in figure 5(a), as physical capital is the source of pollution.

The education sector influences the productivity of human capital and thereby the steady state pollution level. Hence, government interventions like investments in education not only increase the productivity of human capital $B$, but also contribute to enhance environmental quality. Nevertheless, figure 6 shows that an increase in the efficiency of the education sector, $B$, unequivocally leads to a decrease in the share of human capital devoted to abatement activity. Due to the productivity gain, 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, $1 - \nu$, decreases. But simultaneously, the increase in $B$ implies a rise in abatement expenditures and in the human capital intensity in production. Both effects lead to a decrease in the pollution level which dominates the overall impact for all relevant parameter settings, as shown in figure 5(b).

Another possible development strategy is to support technological progress in the abate-
ment sector which leads to an increase in the force of human capital in pollution abatement. In our model, this change is represented by a rise in the parameter $\eta$. With the increase in human capital intensity of abatement technology, the quality of abatement activities rises. There is a transition from quantity, the fraction of total output, to quality of the abatement technology. Abatement expenditures get less important and are substituted by relatively more effective human capital. The pollution level will either increase or decrease as a consequence of enhanced efficiency of human capital in pollution control, depending on the productivity $B$ in the education sector, as will be derived subsequently.

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 (18). 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, $(1 - \eta)h$. 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 19), there is a negative impact as displayed in figure 7(a). With an increase in $\eta$, relative importance of abatement expenditures, $1 - \eta$, decreases. Therefore abatement expenditures decrease and lead to a
higher pollution level.

![Graphs showing abatement ratio e/k, human capital ratio vh/k, and human capital allocation](image)

**Figure 7: Impact of technological change, \( \eta \);**

parameters: \( \alpha = 0.7, \gamma = 0.2, \rho = 0.03, \sigma = 3, A = 1, B = 0.05 \)

The effect of increasing \( \eta \) on the optimal ratio between physical capital and human capital in the production sector is positive and shown in figure 7(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 economy increases and \( \frac{v_h}{k} \) 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 \( \frac{(1 - v)}{v} \) in pollution (18) is given in figure 7(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, two of three effects discussed so far lead to reduced pollution. Decreased physical capital intensity and reallocation of human capital in favour of pollution control foster environmental conservation. In contrast, decreased abatement expenditures indicate less importance of the quantity in abatement activities and induce divergent effects on environmental quality. The overall impact of \( \eta \) on pollution depends on the productivity of human capital accumulation, \( B \), relative to the productivity of the production sector, \( A \), as demonstrated in figure 8.
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 abatement expenditures and enhances efficiency of human capital in pollution control, may increase the pollution level, see figure 8(a). This will happen whenever the pollution increasing effect of declining abatement expenditures overcompensates the pollution decreasing effect induced by the adjustment of physical capital intensity and human capital allocation as described above.

If instead the productivity of human capital accumulation, $B$, 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 8(c). 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. The inverted U in figure 8(b) demonstrates that with an intermediate productivity $B$ of the education sector the technological progress in abatement technology must be sufficiently strong in order to end up in an improvement of environmental quality.

These results can be applied to economies at different development stages. Usually, lower productivity of human capital is along with a less developed education sector and finally with a relatively less developed country. For these economies, environmental protection is based predominantly on quantitative abatement activities. Efficiency improving political reforms in the education sector will enhance environmental quality as a by-product and are with this respect preferable to technological progress in the abatement sector, $\eta$, (and to productivity gains in the production sector, $A$).

The situation is different for relatively more developed countries with a relatively higher
productivity of human capital, $B$. For these economies, there is no need to improve the education sector to reduce the pollution level significantly. Here the politics should support research and development directed to abatement technology in order to increase the quality of the environmental measures. Hence, our results also contribute to the explication why in a wide range of developing economies the increase in the efficiency of human capital in pollution control does not lead to enhanced environmental protection.

6 Conclusion

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.

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. 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 the individually perceived impact on pollution, together with greener preferences, lower the resulting pollution level.

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. We consider different development stages and deduce different supporting opportunities.

Technological change is specified to increase the productivity of human capital or to increase the efficiency of human capital in the abatement technology. We have in mind
that technological change improves the education sector or enables better techniques for pollution control. However, both strategies differ crucially in the resulting impact on the pollution level. Regarding a relatively less developed economy with a lower productivity in the education sector, the preferable strategy is an improvement of the education sector. Beside the obvious positive impact on income per capita, we find additional positive effects on the environment. These are mainly driven by the increase in human capital intensity in the economy as well as increased abatement expenditures.

Nevertheless, a more developed economy with a higher productivity in the education sector will benefit more from research and development directed to the abatement technology. If this improves the productivity of human capital within pollution abatement, the quality of abatement activities increases. Human capital allocation is shifted towards the abatement sector and supports the decrease in the steady state pollution level.

**Appendix: Derivation of parameter restrictions**

In the following, we show that the parameter restriction \( \alpha(1 + \gamma \delta(1 - \eta)) > \gamma \delta \) is a sufficient condition for the existence of a steady state with constant pollution level. Particularly, \( \alpha(1 + \gamma \delta(1 - \eta)) > \gamma \delta \) is a sufficient condition for \( \alpha(1 + \gamma \delta(1 - \eta)) > \gamma \delta \) and \( \frac{v h}{k}^{1 - \alpha} \) as given in equations (21) and (20) to be positive. With these two conditions, the marginal return of capital, net of abatement expenditures, as given in (17) is positive.

First, we show that \( \alpha(1 + \gamma \delta(1 - \eta)) > \gamma \delta \) is a sufficient condition for \( (1 - v)/v \) to be positive. With \( \sigma > \alpha \) the nominator will always be positive. The denominator as given in (21) is positive too, because

\[
(1 + \gamma \delta (1 - \eta)) > \frac{\gamma \delta}{\alpha}
\]

\[
\implies (\sigma B + \rho)(1 + \gamma \delta (1 - \eta)) - \gamma \delta B > (\sigma B + \rho) \frac{\gamma \delta}{\alpha} - \gamma \delta B
\]

\[
\implies (\sigma B + \rho)(1 + \gamma \delta (1 - \eta)) - \gamma \delta B > \frac{\gamma \delta}{\alpha}((\sigma B + \rho) - \alpha B)
\]

\[
\implies (\sigma B + \rho)(1 + \gamma \delta (1 - \eta)) - \gamma \delta B > \frac{\gamma \delta}{\alpha}(B(\sigma - \alpha + \rho)) > 0
\]  

(23)

Second, we show that \( \alpha(1 + \gamma \delta(1 - \eta)) > \gamma \delta \) is a sufficient condition for \( \frac{v h}{k}^{1 - \alpha} \) accord-
ing to (20) to be positive:

\[
\alpha(1 + \gamma \delta(1 - \eta)) > \gamma \delta
\]

\[
\Rightarrow -\alpha (1 + \gamma \delta(1 - \eta)) B < -\gamma \delta B
\]

\[
\Rightarrow (\sigma B + \rho)(1 + \gamma \delta(1 - \eta)) - \alpha(1 + \gamma \delta(1 - \eta))B < (\sigma B + \rho)(1 + \gamma \delta(1 - \eta))B - \gamma \delta B
\]

\[
\Rightarrow (1 + \gamma \delta(1 - \eta))(\sigma B + \rho - \alpha B) < (\sigma B + \rho)(1 + \gamma \delta(1 - \eta)) - \gamma \delta B
\]

\[
\Rightarrow \gamma \delta(\sigma B + \rho - \alpha B) > \gamma \delta(\sigma B + \rho - \alpha B)
\]

\[
\Rightarrow \gamma \delta(1 + \gamma \delta(1 - \eta)) < (\sigma B + \rho)(1 + \gamma \delta(1 - \eta)) - \gamma \delta B
\]

\[
\Rightarrow \alpha > \frac{\gamma \delta}{1 + \gamma \delta(1 - \eta)} > \frac{\gamma \delta(\sigma - \alpha) + \rho}{(\sigma B + \rho)(1 + \gamma \delta(1 - \eta)) - \gamma \delta B}
\]

(24)

Last, we show that (24) immediately implies that the marginal return of capital, net of abatement expenditures, as given in (17) is positive:

\[
\alpha > \frac{\gamma \delta(\sigma - \alpha) + \rho}{(\sigma B + \rho)(1 + \gamma \delta(1 - \eta)) - \gamma \delta B}
\]

\[
\Rightarrow \frac{\eta}{1 - \alpha} > \frac{\gamma \delta(\sigma - \alpha) + \rho}{(\sigma B + \rho)(1 + \gamma \delta(1 - \eta)) - \gamma \delta B} \frac{\eta}{1 - \alpha}
\]

\[
\Rightarrow \alpha - \frac{1 - \alpha}{\eta} > \frac{1 - \nu}{\nu}
\]

\[
\Rightarrow \alpha - \frac{1 - \alpha}{\eta} > \frac{1}{\nu}
\]

\[
\Rightarrow A \left( \frac{\nu h}{k} \right)^{1 - \alpha} \left( \alpha - \frac{1 - \alpha}{\eta} \frac{1 - \nu}{\nu} \right) > 0
\]

(25)

**References**


