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ENVIRONMENTAL QUALITY AND POLLUTION-SAVING TECHNOLOGICAL CHANGE IN A TWO-SECTOR ENDOGENOUS GROWTH MODEL

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Abstract

This paper explores the link between environmental quality and economic growth in an endogenous growth model that incorporates pollution-saving technological change. It examines the conditions under which sustainable growth is both feasible and optimal. We explore also how the government should intervene to ensure the optimal levels of natural and knowledge capital, which have a public-goods character. Furthermore, the long-run effects of an increased concern for the environment are examined. In particular, we establish the conditions for a more ambitious environmental policy to raise long-run growth.

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1 Introduction

Does a better quality of the natural environment require lower economic growth? Does economic growth constitute a fatal threat to the natural environment? These controversial issues often feature in discussions about environmental policy, in general, and sustainable growth, in particular. Pessimists argue that the natural environment can survive only at zero or negative growth rates. Optimists, in contrast, maintain that high rates of growth can be compatible with a clean environment. Indeed, in their view, 'win-win' opportunities (see, e.g. World Bank (1992)) often exist in which policy can simultaneously enhance environmental quality and productive capacity.

This paper explores the link between environmental quality and sustainable economic growth. In particular, we examine the conditions under which growth in physical output is sustainable and compatible with a stable quality of the natural environment. We also investigate which policy instruments the government should adopt to ensure that a decentralized market economy reaches a sustainable growth path. Finally, we investigate how an increase in environmental concern affects the long-term rate of growth.

We develop a two-sector endogenous growth model in which economic activity depends on the extractive use of the natural environment which is modeled as a renewable resource. In particular, production requires inputs that inevitably pollute the environment (e.g. pesticides in agriculture, fossil fuels resulting in emissions of carbon) or that directly harvest nature (e.g, water, wildlife, fish, wood, etc.). This extractive use of the environment adversely affects environmental quality. The pollution-assimilating and self-generating capacities of the environment, however, allow for a certain sustainable flow of pollution, which matches the biological regeneration rate. The stock of natural resources has a positive value because its amenity enters utility (e.g. the effect of air quality on health, the aesthetic value of unspoiled landscapes). Moreover, the environment has a productive role in that it yields public non-extractive services that act as an input into production (the carrier services of the environment, which supply physical and mental support to productive activities, e.g. the impact of soil and air quality on productivity in the agricultural sector and on labor productivity, more generally).

Neo-classical growth models have been employed to study the link between environmental policy and economic growth (see, e.g. Foster (1973), Van der Ploeg and Withagen (1991), and Tahvonen and Kuuluvainen (1991)). We extend this literature in two directions. First, in traditional neo-classical models, (environmental) policies do not impact long-run growth because reproducible factors exhibit diminishing returns. Hence, if the reproducible inputs grow relative to the non-reproductable factors, their marginal products eventually fall back to zero. The long-run growth rate is thus exogenously determined by the growth rate of the non-reproducible inputs (e.g. labor, natural resources). We, in contrast, assume – in the spirit of the so-called 'new' growth theory – that reproducible factors do not necessarily feature diminishing returns (see also Ligthart and Van der Ploeg (1992)). In this way, the steady-state growth rate becomes endogenous. Hence, environmental policy may impact long-run growth.

The second extension of the literature on growth and the environment involves the modeling of endogenous pollution-saving technological progress. Building on the work of Lucas (1988) and Rebelo (1991), we model the development of new technical knowledge that enables production to occur in a less polluting way and to use renewable resources more efficiently. Within this framework, there are two reasons for government intervention, namely that both environmental quality and pollution saving knowledge have a public good character. We find that, on an optimal balanced growth path, the revenues from pollution taxes (or pollution permits) exceed public expenditures on the development of pollution-saving technology, and that the optimal size of the government budget tends to increase with growing environmental concern.

A more ambitious environmental policy affects the long-run rate of growth in two opposing directions. On the one hand, allowing a lower level of polluting inputs and harvested resources implies a fall in the productivity of reproducible inputs, thereby hurting growth. On the other hand, the reduction in pollution improves the quality of the environment, which positively affects productivity and growth. The second effect may outweigh the first if environmental quality not only enters utility but also has an important productive role.

The paper is structured as follows. Section 2 presents the model and derives the optimum conditions for a command economy. The feasibility and optimality of balanced growth requires particular conditions on technology and preferences. These conditions are derived in Section 3. Section 4 explores how the government should intervene in a market economy to ensure the optimal allocation. Section 5 examines the steady-state effects of a more ambitious environmental policy, which is associated with a decline in economy-wide pollution, on a number of variables such as on economic growth, the real rate of return, the bias of technological change as indicated by the knowledge-intensity of production, the ratio of consumption to assets, and the ratio of public to private spending. Section 6 demonstrates that an increase in environmental concern is associated with a lower optimal pollution level. Accordingly, the results contained in Section 5 can be interpreted as the long-run effects of a shift toward 'greener' preferences. Finally, Section 7 contains the conclusions.

2 The model

Environmental quality

Economic activity is embedded in the natural environment, which is modeled as a renewable resource. The quality of the natural environment N, which is the stock of natural capital, accumulates due to the regenerative capacity of nature while it depreciates on account of the damaging effects of pollution P. Here, N evolves over time according to the following regeneration function (see Tahvonen and Kuuluvainen (1991)):

$$\dot{N} \equiv \frac{dN}{dt} = E(N,P) \qquad \begin{array}{l} E_P < 0 \quad E_{PP} < 0 \\ E_{NN} < 0 \quad E_{NP} < 0 \\ E(\bar{N}(P),P) = 0 \end{array} \tag{2.1}$$

The dot represents a time derivative. The subscripts attached to the function symbol E denote partial derivatives.

For each level of pollution (or emissions) P, there exists a stable level of environmental quality $\bar{N}$ for which nature regenerates itself such that environmental quality remains constant over time. Raising the level of pollution, which can be interpreted as increasing the rate of harvest of the renewable resource, reduces the regenerative capacity (or absorption capacity) of the environment, causing N to fall to a lower level (i.e. $\frac{d\bar{N}(P)}{dP} < 0$). For this level to be stable, it is assumed that $E_N(N, P) < 0$ around $\bar{N}(P)$. This implies that natural capital becomes more productive as a nature regenerating kind of capital if it becomes scarcer. Starting from a very low natural capital stock ($N << \bar{N}$), a rise in N is likely to increase the absorption capacity ($E_N(N, P) > 0$). After a certain point, however, congestion (e.g. overpopulation) occurs and, hence, the regenerative capacity declines with N (see Figure 1).

Production

Two sectors make up the production side of the economy (as in Lucas (1988) and Rebelo (1991)). One sector produces a final output that can be either consumed or invested for the purpose of accumulating capital. Accordingly, we call this sector the final- or consumption-goods sector or, alternatively, the capital-producing sector.

The second sector, which we name the knowledge- or learning sector, generates knowledge about pollution-saving techniques. It is a pure 'investment sector' because the output is not used for consumption but only for the purpose of accumulating technological knowledge.

The final good, Y, is produced according to the following technology:

$$Y = Y(N, K_Y, Z_Y) \tag{2.2}$$

The first input is the aggregate stock of natural capital (N). Clean soil and air provide productive services to economic activities (e.g. healthy workers, small physical depreciation of equipment). The second input, K_Y, represents the stock of 'manmade' capital allocated to the final goods sector. Capital K is interpreted as a broad measure of capital. It includes all capital that can be produced [and accumulated by allocating resources to economic activities], such as physical capital and human capital. However, it excludes knowledge capital directly related to pollution. For convenience we label K as physical capital.

The third input, Z_Y, represents effective input of 'harvested' environmental resources in the consumption goods sector. No production is feasible without pollution. However, pollution-saving technical progress is possible. In particular, the productive content of pollution depends on the available knowledge about pollution-saving techniques, represented by h. Therefore, Z_Y can be written as vhP where P stands for the economy-wide level of pollution (which affects the quality of the environment, see equation (2.1)), $hP \equiv Z$ represents the 'effective' level of pollution that is productive in economic activities, and v is the share of effective pollution for which the final goods sector is responsible.

The stock of knowledge h is separated from the kinds of 'man-made' capital included in K, so that we can explicitly study the role of pollution-saving technology. The accumulation of pollution-saving knowledge requires investment in the learning sector. In particular, the following technology describes the growth of technical knowledge:

$$\dot{h} = H = H(K_H, Z_H) - \delta_H h \tag{2.3}$$

where δ_H stands for the depreciation rate of technological knowledge. The inputs into the knowledge sector are physical capital (K_H) and effective pollution ($Z_H = (1-v)hP$).

Summing up, the model incorporates three kinds of capital: natural capital (N), 'physical' capital (K), and pollution-saving knowledge capital (h). N and h are accumulated according to equations (2.1) and (2.3) respectively, while a standard accumulation equation links the evolution of the stock of economy-wide physical capital to investment, $Y - C$:

$$\dot{K} = Y - C - \delta_K K \tag{2.4}$$

where C denotes consumption and δ_K represents the rate of physical depreciation. Besides distinguishing between natural capital (N) and 'man-made' capital (h and K), one can distinguish between rival capital (K) and nonrival capital (N and h). Physical capital, K, (as well as pollution, P) is rival in the sense that each unit can be employed in only one of the two sectors. The allocation of the total stock $K = K_H + K_Y$ is characterized by $u \equiv K_Y/K$ (cf. $v \equiv Z_Y/Z$). Technological knowledge h is non-rival; it increases production in both sectors.

Preferences

The economy is populated by L identical infinitely-lived individuals with preferences over consumption goods and environmental quality:

$$\int_0^\infty e^{-\theta t} U(c(t), N(t)) dt \tag{2.5}$$

where θ represents the rate of time preference and $c = C/L$ denotes per capita consumption. As a non-rival good, N features in both production (2.2) and individual utility (2.5).

Optimal static allocation

Given the total amount of capital ($K = K_Y + K_H$) and effective pollution ($Z = Z_Y + Z_H$), the optimal sectoral allocation of both rival factors at any moment in time is governed by:

$$\frac{\partial Y}{\partial K_Y} = q_h \frac{\partial H}{\partial K_H} \tag{2.6}$$

$$q_Z \equiv \frac{\partial Y}{\partial Z_Y} = q_h \frac{\partial H}{\partial Z_H} \tag{2.7}$$

where q_h denotes the shadowprice of knowledge relative to physical capital and q_Z can be interpreted as the shadow price of effective pollution. The first (second) condition states that the marginal product of physical capital (effective pollution), measured in terms of units of physical capital, should be the same in the two sectors.

The decision on the optimal level of pollution, given the optimal allocation, is also of a static nature. Optimality requires that the marginal benefit of pollution (in both sectors) equals its marginal cost, which is the deterioration of the quality of the environment N:

$$q_Z h = -E_P q_N \tag{2.8}$$

where q_N stands for the shadowprice of N relative to that of K.

Optimal dynamic allocation

Investment in the three kinds of capital (K, h and N) should be traded off against each other and against consumption:

$$r = \frac{\partial Y}{\partial K_Y} - \delta_K = \frac{\partial H}{\partial Z_H} P + \frac{\dot{q}_h}{q_h} - \delta_H = \left(L \frac{\partial U}{\partial N} / \frac{\partial U}{\partial c} + \frac{\partial Y}{\partial N} \right) \frac{1}{q_N} + \frac{\dot{q}_N}{q_N} - \delta_N \tag{2.9}$$

$$r = \theta + \frac{\dot{L}}{L} - \frac{\dot{U}_c}{U_c} \tag{2.10}$$

where $\delta_N \equiv -E_N(N, P)$, which is positive around $\bar{N}$, can be interpreted as the depreciation rate of natural capital. Arbitrage condition (2.9) reveals that K, h and N should yield the same return. The return on capital amounts to its marginal product (i.e. the dividends or current benefits, which are equal in both sectors as required by the optimal sectoral allocation (2.6)) minus depreciation. Dividends and depreciation also feature in the return on knowledge, but here also changes in the relative price (i.e. capital gains) should be taken into account. Furthermore, the marginal product of effective pollution is multiplied by economy-wide pollution P. This reflects the non-rival nature of knowledge. Also the return on natural capital consists of dividends, capital gains and a depreciation allowance. Since natural capital is nonrival in nature, dividends amount to the *sum* of the marginal benefits of natural capital in individual utility and production.

Equation (2.10) stands for the well-known Ramsey rule representing the trade-off between investment and consumption. Postponement of consumption must be rewarded by a rate of return that compensates for the pure rate of time preference, the rate of population growth (which decreases *ceteris paribus* per capita consumption), and the change over time in the (marginal) value of consumption (U_c).

3 Conditions for balanced endogenous growth

Growth in output can be achieved by investing in knowledge as well as natural and physical capital and by increasing pollution. We focus on balanced growth, defined as a situation in which allocative variables ($u \equiv K_Y/K, v \equiv Z_Y/Z, C/Y$) are constant and in which all other variables change at constant (possibly zero) rates. This requires some restrictions on ecological relationships, technology and preferences.

Ecological relationships

Since we assume that the environment evolves according to (2.1), the stock of environmental services can grow at a constant rate only if pollution is reduced at an accelerating rate. Hence, on a balanced growth path, the quality of the environment, N, and the aggregate level of pollution, P, have to be constant.

Technology

With $P, N, C/Y, u$ and v constant, growth in output is fuelled by sustained increases in knowledge and physical capital. The relative change in the growth rates of these two assets can be written as:

$$\frac{\dot{g}_h}{g_h} = \lambda_{K_H}\frac{\dot{K}}{K} + (\lambda_{Z_H} - 1)\frac{\dot{h}}{h} \tag{3.1}$$

$$\frac{\dot{g}_K}{g_K} = (\lambda_{K_Y} - 1)\frac{\dot{K}}{K} + \lambda_{Z_Y}\frac{\dot{h}}{h} \tag{3.2}$$

where g_j denotes the growth rate of j and λ_i stands for the production elasticity of factor i. Balanced growth requires $\dot{g}_h = \dot{g}_K = 0$ or equivalently (cf. Mulligan and Sala-i-Martin

(1992)):

$$\frac{\lambda_{K_H}}{1-\lambda_{Z_H}} = \frac{1-\lambda_{K_Y}}{\lambda_{Z_Y}} = \frac{g_h}{g_K} \tag{3.3}$$

This condition has implications for the elasticities of substitution and the degrees of economies of scale in both sectors. In a situation of balanced growth, natural capital becomes scarcer relative to the production factors K_Y and Z_Y, since it remains constant while K and h grow steadily. If natural capital is a production factor in the Y-sector ($\partial Y/\partial N > 0$, see (2.2)), the production elasticities λ_{K_Y} and λ_{Z_Y} change over time unless the elasticity of substitution between, on the one hand, natural capital and, on the other hand, physical capital and effective pollution is unity. Since balanced growth requires (3.3) to be satisfied at each moment in time, production elasticities should be constant.[1] Accordingly, the elasticity of substitution between natural capital and the other production factors should equal one.

As far as economics of scale are concerned, either both sectors should exhibit constant returns to scale with respect to physical capital and effective pollution (CRS), or decreasing returns to scale (DRS) in one sector should be compensated by increasing returns to scale (IRS) in the other (e.g. if the ratio (3.3) exceeds 1, and the growth of knowledge thus exceeds growth of physical capital, the knowledge sector exhibits IRS, $\lambda_{K_h}+\lambda_{Z_h} > 1$, while the consumption good sector features DRS, $\lambda_{K_Y}+\lambda_{Z_Y} < 1$). If both sectors would exhibit DRS, the marginal productivity of both factors would decline and growth would thus vanish. With IRS in both sectors, in contrast, growth rates would accelerate.

With CRS in both sectors, capital and knowledge grow at a common rate (i.e. $g_K/g_h = 1$). Hence, the production elasticities λ_i remain constant over time, irrespective of the elasticity of substitution between effective pollution and capital in the Y-sector (denoted by σ_Y) and the corresponding elasticity in the H-sector (denoted by σ_H).

[1]Strictly speaking, only the ratios in (3.3) should be constant. Assuming a production function that is homogeneous of (a fixed) degree γ in K and Z, we can write the ratio as: $(1-\lambda_{K_Y})/\lambda_{Z_Y} = 1+(1-\gamma)/\lambda_{Z_Y}$ since by definition $\gamma \equiv \lambda_{K_Y}+\lambda_{Z_Y}$. Accordingly, either the production elasticities λ_i have to be constant or the production function should exhibit CRS in K and Z (i.e. $\gamma = 1$).

However, if one sector exhibits IRS and the other DRS, capital and knowledge grow at different rates (i.e. $g_K/g_h \neq 1$). Consequently, the production elasticities λ_i would change over time, thereby violating (3.3), unless $\sigma_Y = \sigma_H = 1$. Therefore, production functions in both sectors should be of the Cobb-Douglas type for balanced growth to be feasible. If the substitution elasticities would exceed unity, factors of production are good substitutes and the factor produced in the sector exhibiting IRS would gradually replace the other factor. Intuitively, the IRS sector dominates the DRS sector which implies an accelerating growth rate in the long run.[2] If the substitution elasticities would fall short of unity, in contrast, factors of production are poor substitutes. Consequently, the factor produced in the sector exhibiting DRS cannot easily be replaced by the other factor and growth thus slows down.

We focus on the case with CRS (with respect to physical capital and effective pollution)[3] in both sectors and substitution elasticities between physical capital and effective pollution (σ_Y and σ_H) below or equal to one. This represents the case where production cannot take place without pollution (pollution is essential: $\sigma_Y, \sigma_H \leq 1$). Hence, sustained pollution saving technological progress is necessary to keep the economy growing. The production functions in (2.2) and (2.3) can now be specified as:

$$Y = A_Y(N) \cdot F(K_Y, Z_Y), \qquad A_Y' \geq 0, \;\; A_Y'' \leq 0 \tag{3.4}$$

$$\dot{h} = H = A_H \cdot G(K_H, Z_H) \tag{3.5}$$

where, for simplicity we abstract from depreciation of capital or knowledge (i.e. $\delta_K = \delta_H = 0$).

[2]If we would require only asymptotically balanced growth, we could have CRS in one sector and DRS in the other with elasticities of substitution larger than one. Asymptotically the DRS sector vanishes, the CRS sector dominates and growth approximates a constant rate. This is the case explored by Jones and Manuelli (1990). In our setting, we could assume that pollution saving knowledge can be accumulated only subject to DRS, or - as an extreme case - that it cannot be accumulated. In this case, growth could be sustained if pollution is nonessential ($\sigma_Y > 1$) and growth would be asymptotically constant if the Y-sector exhibits CRS. However, pollution would not play any productive role in the long run.

[3]If N enters the Y-sector, the production function for Y features IRS in N, Z_Y and K_Y.

If both sectors exhibit CRS, capital and knowledge grow at a common rate, say g. At the same time, the marginal products of these two factors and the relative price q_h and q_Z remain constant (see (2.7)). However, the fixed factors N and P become scarcer as the economy grows and the marginal productivities of these factors thus grow at rate g. Also, the relative price of the natural environment (q_N) grows at that rate. Hence, balanced growth is characterized by:

$$\frac{\dot{K}}{K} = \frac{\dot{h}}{h} = \frac{\dot{C}}{C} = \frac{\dot{c}}{c} = \frac{\dot{Y}}{Y} = \frac{\dot{q}_N}{q_N} = g, \qquad \dot{N} = \dot{P} = \dot{q}_h = \dot{q}_Z = 0. \tag{3.6}$$

where we ignore population growth ($\dot{L} = 0$).

Preferences

While the restrictions on technology guarantee that a balanced growth path is *feasible*, restrictions on preferences are required to guarantee that balanced growth is *optimal*. Optimal growth is balanced if the rate of return is constant. If C grows at rate g and N remains constant, this requires that:

(i) marginal utility of consumption rises at a constant rate (see the Ramsey rule (2.10))

(ii) the ratio $L\left(\frac{\partial U/\partial N}{\partial U/\partial c}\right)$ increases at the same rate (g) as q_N and $\partial Y/\partial N$ (see the arbitrage condition for N on the right-hand-side of (2.9)).

Marginal utility evolves over time according to

$$\frac{\dot{U}_c}{U_c} = \left(\frac{U_{cc}c}{U_c}\right)\frac{\dot{c}}{c} + \left(\frac{U_{cN}N}{U_c}\right)\frac{\dot{N}}{N}, \tag{3.7}$$

where subscripts denote the partial derivatives of the instantaneous utility function. Marginal utility grows at a constant rate if the intertemporal substitution elasticity ($-U_c/U_{cc}c \equiv \sigma$, see term in the first brackets) is constant, i.e. independent of the scale of consumption and independent of the ratio of N to c. This requires a time-separable constant-relative-risk-aversion (CRRA) utility function. Since C grows at rate g, the second restriction on preferences requires that $(LU_N/U_c) \cdot (N/C) = U_N N/U_c c$ remains constant in the steady state. The elasticity of U_N/U_c with respect to c must be unity. As shown by King, Rebelo and Plosser (1988), this implies that the elasticity of substitution in utility between consumption and some index of environmental services should equal unity.[4] Intuitively, in a growing economy, the shadow price of environmental services rises, thereby providing an incentive to substitute consumption of produced goods for environmental services. The optimal stock of natural capital remains constant only if this negative substitution effect on the demand for environmental services is exactly offset by the positive income effect triggered by output growth. This requires that the elasticity of substitution is unity.

The initial steady-state equilibrium

The shares of capital in the production of final goods and knowledge in the initial equilibrium are denoted by, respectively, $\alpha = \frac{K_Y \frac{\partial F}{\partial K_Y}}{F(K_Y, Z_Y)}$ and $\beta = \frac{K_H \frac{\partial G}{\partial K_H}}{G(K_H, Z_H)}$. On a balanced growth path, the shares u and v can be expressed as (see Appendix A):

$$u \equiv \frac{K_Y}{K} = \alpha \left[\frac{r - g + \beta g}{\alpha(r-g) + \beta g} \right] \tag{3.8}$$

$$v \equiv \frac{Z_Y}{Z} = \frac{(r-g) + \beta g}{r} \tag{3.9}$$

where r and g denote, respectively, the real rate of return and the rate of economic growth. If the interest rate equals the growth rate, the entire output of the capital-

[4] These authors explore a utility function with consumption and leisure (which should be constant in the steady state as N in our case) as arguments. Instantaneous utility that satisfies the required restrictions looks like:

$U = \left(\frac{\sigma}{\sigma - 1}\right) c^{1-1/\sigma} . n(N)$, with $n' > 0$ and $n'' < 0$ if $\sigma > 1$ and $n' < 0$ and $n'' > 0$ if $\sigma < 1$.

producing sector is invested (i.e. $C = 0$)[5]. In that case, the fraction of capital allocated to the capital-producing sector, u, corresponds to the share of capital in that sector, α. At the same time, the pollution share in the knowledge-creating sector, $1-\beta$, equals the fraction of economy-wide pollution employed in that sector, $1 - v$. If the interest rate exceeds the growth rate and consumption thus becomes positive, the fractions of the two rival production factors employed in the consumption-good sector rise (i.e. $u > \alpha$ and $v > \beta$). Indeed, these shares are related positively (see also Mulligan and Sala-i-Martin (1992)). Hence, an increase in the share of capital allocated to the consumption-good sector is associated with a larger share of pollution employed in that sector.

The fractions u and v are linked to the shares α and β according to (from (3.8) and (3.9)):

$$\left(\frac{v-u}{u}\right) = \left(\frac{\beta-\alpha}{\alpha}\right)\left(\frac{g}{r}\right) \tag{3.10}$$

Expression (3.10) reveals that a relatively large fraction of economy-wide pollution is allocated to the pollution-intensive sector. In the rest of this paper we will generally assume that the consumption-good sector is relatively pollution intensive ($\beta > \alpha$). In that case, the fraction of aggregate pollution allocated to this sector, v, exceeds the corresponding fraction of economy-wide capital employed in that sector, u.

4 Market equilibrium

Without government intervention, the decentralised market economy suffers from two market failures, which are associated with the public-good character of the environment N and knowledge h. These goods are not provided in a pure market economy. With respect to the natural environment, each individual consumer and each individual producer in the final goods sector benefits from the quality of the environment (i.e. $\partial U/\partial N > 0$ and $\partial Y/\partial N \geq 0$). However, since this quality depends on *aggregate* pollution, individual

[5] See expression (C.7) in Appendix C.

consumers and producers ignore the effects of their decisions on N. Indeed, without government intervention, producers would face no cost at all associated with pollution, but only a benefit ($\partial Y/\partial Z_Y > 0$ and $\partial H/\partial Z_H > 0$). Therefore, they would select an infinitely large level of pollution. As a consequence of the tragedy of the commons, the quality of the environment would decline to unsustainably low levels and neither production nor life would be possible. Social mechanisms are needed to prevent this. For example, the government may levy tax on emissions. Alternatively, it may create the missing market for pollution permits by auctioning off such permits.

Knowledge h is a nonrival and thus a public good. The cost of acquiring knowledge is a fixed cost; once acquired the knowledge can be applied at any scale of operation. The existence of fixed costs implies economies of scale so that perfect competition is not viable. Or, to put in another way, if perfect competition were present, after paying the rival factors of production their marginal product (including the tax on pollution) no quasi-rent would be left to pay for h. Hence, pollution saving technological innovation would not be rewarded and thus no research would be undertaken. Accordingly, the government should pay for the development of new technology and freely provide the knowledge to firms.

The government thus needs to intervene to ensure the optimal levels of the two public goods N and h. The provision of N yields public revenue as the government charges a cost for the use of the environment. The development of pollution-saving knowledge, in contrast, absorbs public means. It is of some interest to explore the relative magnitudes of revenues and expenditures associated with optimal environmental policy.

Firms equate the marginal product of pollution, given the available pollution saving technology, to the cost of pollution:

$$\frac{\partial Y}{\partial Z_Y} h = \tau_P \tag{4.1}$$

where τ_P denotes the pollution tax, which can alternatively be interpreted as the price of pollution permits. Combining this equilibrium condition with optimality condition

(2.7), we find for the optimal tax on pollution:

$$\tau_P = q_Z \cdot h \tag{4.2}$$

In the steady state, the optimal tax rises at rate $\dot{h}/h = g$ to prevent pollution from rising and the environment from deteriorating. Sustained innovation raises the marginal productivity of pollution. This provides an incentive to increase pollution unless the pollution tax rises at the same rate.

The price (in terms of final goods) that the government pays for new technology equals the shadow price q_h. Hence, total public spending amounts to $q_h H = q_Z H / \frac{\partial H}{\partial Z_H}$ (using (2.7)). This yields the following balance between tax revenues and research spending:

$$q_Z \left[Z - \frac{H}{\partial H / \partial Z_H} \right] = q_Z Z \left(\frac{v - \beta}{1 - \beta} \right) \tag{4.3}$$

where we used the definitions of $1 - \beta = \left(Z_H \frac{\partial H}{\partial Z_H} / H \right)$ and $1 - v = Z_H / Z$. Since $v > \beta$ if steady-state consumption is positive, revenues from pollution taxes (or auctioned pollution permits) are more than sufficient to finance research subsidies. The intuition is as follows. Pollution and publicly provided knowledge are perfect substitutes in production. Hence, the pollution tax, which corresponds to the shadow price of pollution, directly measures the return on the stock of knowledge. At the same time, the optimal subsidy corresponds to the cost of investing in this stock. As a kind of golden rule for the stock of knowledge, it is optimal to invest only part of the returns and, thus, tax revenues should exceed R&D spending on the optimal balanced growth path. Accordingly, the government should earmark only part of the pollution tax revenue for developing pollution saving knowledge capital. Moreover, the public goods can be entirely financed by non-distortionary taxes. This is in contrast to Barro (1990).[6]

[6] If α equals β, u and v are equal at each point in time (see (3.10)). In that case, we can interpret $1 - u = 1 - v$ as the share of output devoted to the production of the public input. This model resembles that of Barro (1990). The main difference is that the public input is a stock of public capital that needs to be accumulated rather than instantaneous public services.

5 Exogenous environmental policy

This section discusses the comparative statics of the steady-state solutions for sectoral factor intensities (Subsection 5.1), the real rates of return and growth (Subsection 5.2), the allocation of the rival inputs across the two sectors (Subsection 5.3), the direction of technological change as measured by the capital-knowledge ratio K/h (Subsection 5.4), the ratio of consumption to capital and knowledge (Subsection 5.5), the tax on pollution (Subsection 5.6), the price of knowledge (Subsection 5.7), and the ratio of public to private spending (Subsection 5.8). Each subsection starts by exploring the long-run effects of shocks in the productivity parameters A_Y and A_H. This discussion sets the stage for the investigation of the steady-state impact of an exogenous reduction in economy-wide pollution. Hence, in this section environmental policy is exogenous in the sense that the amount of pollution is not set optimally. However, Section 6 shows that the cut in pollution analyzed in Section 5 can be interpreted as an endogenous response to a change in preferences towards more environmental concern. When investigating the consequences of cutting pollution, we first examine the case in which environmental quality leaves production unaffected (i.e. $dA_Y/dN = 0$) before exploring the case in which environmental quality features as a production factor in the consumption-goods sector (i.e. $dA_Y/dN > 0$). In this latter case, pollution affects long-run productivity according to (see Appendix D):

$$\tilde{A}_Y = -a_Y \left(\frac{E_P P}{E_N N}\right) \tilde{P}$$

where a tilde ˜ denotes a relative change and where a_Y is the elasticity of A_Y with respect to N:

$$a_Y \equiv \frac{(dA_Y/dN)N}{A_Y}.$$

Table 1 contains a summary of the findings in this section.

5.1 Sectoral factor-intensities

The long-run solutions for the sectoral capital-effective pollution ratios are given by (see Appendix A):

$$\frac{1}{\sigma_Y}\left(\tilde{K}_Y - \tilde{P}_Y\right) = \frac{1}{\sigma_H}\left(\tilde{K}_H - \tilde{P}_H\right) = \left(\frac{\tilde{A}_Y - \tilde{A}_H - \tilde{P}}{1-\alpha+\beta}\right) \tag{5.1}$$

Productivity shocks

The factor produced by the more productive sector becomes more abundant. Accordingly, production becomes more intensive in that factor. The sectoral substitution elasticities (σ_Y and σ_H) and the shares α and β determine the magnitude of the impact on the sectoral factor intensities. The larger the sectoral substitution elasticity, the more a sector is able to absorb the more abundant production factor and thus the larger is the impact of a relative productivity shock on the sectoral factor mix.

The sensitivity of the sectoral capital-effective pollution ratio with respect to relative productivity shocks depends also on the share of pollution in the capital-producing sector, $1-\alpha$, and the share of capital in the knowledge-producing sector, β. These shares are called 'cross-shares' because they reflect the importance of capital and effective pollution in the accumulation of the other production factor. Large cross shares mitigate the impact of relative productivity shocks on the sectoral factor intensities. The reason is that large cross shares imply that a more productive production process not only results in more accumulation of the factor produced by that sector but also indirectly yields more of the factor produced by the other sector as the more abundant factor plays an important role in the production of the other production factor.

Environmental policy ($\tilde{P} < 0$ with $a_Y = 0$)

Environmental policy ($\tilde{P} < 0$) causes production to become less pollution intensive. How much the sectoral capital-effective pollution ratio rises depends on the sectoral substitution elasticity. If this substitution elasticity is large, substituting away from pollution is relatively easy and production in that sector becomes substantially less pollution intensive.

Large cross-shares (i.e. $1-\alpha$ and β are large and thus $1-\alpha+\beta$ is large) reduce the effect of environmental policy on the sectoral factor intensities. Intuitively, if factors play an important role in the accumulation of the other factor, the model becomes 'more stable' in the sense that changes in the relative abundance of the production factors exert a smaller impact on the factor-intensity of production. In particular, lower pollution not only directly reduces effective pollution but also indirectly inhibits the accumulation of capital if the pollution share in the capital-producing sector, $1-\alpha$, is large. The accumulation of pollution-saving technological knowledge, in contrast, is not much reduced by environmental policy if pollution is not an important input in producing that knowledge (i.e. $1-\beta$ is small). Accordingly, the second-round effects mitigate the impact of environmental policy on sectoral factor intensities if pollution plays an important role in the accumulation of capital and at the same time does not feature a large share in the accumulation of knowledge.

Environment as production factor ($\tilde{P} < 0$ with $a_Y > 0$)

Production becomes even less pollution intensive if a better environmental quality facilitates the production of capital. The reason is that a lower level of pollution raises the long-run quality of the environment, thereby boosting the productivity of the capital-producing sector and thus increasing the supply of capital. Accordingly, the capital-effective pollution ratio rises on account of not only lower (effective) pollution but also a larger stock of produced capital. Intuitively, production relies less on pollution P and more on natural and produced capital (N and K).

5.2 Real return and growth

The steady-state version of the Ramsey rule (2.10) governing the intertemporal allocation of consumption links the real return r to growth g:

$$r = \theta + \frac{g}{\sigma} \tag{5.2}$$

Log-linearizing this expression, we find:

$$\tilde{g} = \tilde{r} + \sigma\left(\frac{\theta}{g}\right)\tilde{r} = \tilde{r} + \left(\frac{\theta}{r-\theta}\right)\tilde{r} \tag{5.3}$$

The effect on economic growth is directly related to the impact on the real return. Growth is especially sensitive to the real return if the intertemporal elasticity, σ, and the rate of time preference, θ, are large. The effect on the real return is given by (see Appendix A):

$$\tilde{r} = \left[\frac{\beta}{1-\alpha+\beta}\right] \tilde{A}_Y + \left[\frac{1-\alpha}{1-\alpha+\beta}\right] (\tilde{A}_H + \tilde{P}) \tag{5.4}$$

Productivity shocks

The effect of productivity shocks on the real return (5.4) is closely related to the result derived by Rebelo (1991) for the case of Cobb-Douglas production functions. Rebelo found that the long-run real return depends on the geometric average of the two productivity parameters A_Y and A_H with the same weights as in (5.4). Expression (5.4) generalizes Rebelo's result to production functions with non-unitary substitution elasticities. It reveals that non-unitary substitution elasticities do not affect the impact of productivity shocks on the real return. On the one hand, small substitution elasticities imply that relative productivity shocks exert only a small impact on sectoral factor intensities (see expression (5.1)). On the other hand, however, the rate of return becomes more sensitive to changes in factor intensities if substitution becomes more difficult. These two effects exactly offset each other.

The relationship between the real return and productivity is one-to-one if both sectors feature the same productivity shocks ($\tilde{A}_Y = \tilde{A}_H$). The macro-economic impact of sectoral productivity shocks depends on the relative magnitude of the cross shares; a productivity shock in a particular sector exerts a more substantial impact on the economy-wide return, the larger is the cross share of the factor produced by that sector compared to the cross share of the other factor. The intuition is as follows. Long-term arbitrage between investment in capital and knowledge requires that the rates of return on the two types of investment are equal (see expression (2.9)):

$$\frac{\partial Y}{\partial K_Y} = P\frac{\partial H}{\partial Z_H} = r \tag{5.5}$$

If a productivity shock $\tilde{A}_Y > 0$ raises the return on capital, $\frac{\partial Y}{\partial K_Y}$, the equality between the two returns in (5.5) is re-established by making production more capital-intensive. More capital-intensive production reduces the rate of return on capital, $\frac{\partial Y}{\partial K_Y}$, while at the same time raising the return on knowledge, $P\frac{\partial H}{\partial Z_H}$. If pollution is an important input in the production of capital (i.e. α is small), the rate of return on capital declines rapidly if production becomes more capital intensive. If at the same time, the share of capital in the production of knowledge, β, is small, the rate of return on knowledge rises only slowly. Accordingly, the arbitrage condition (5.5) is met at a relatively low return. Accordingly, the productivity shock in the capital-producing sector is not very powerful in raising the macro-economic rate of return and thus the growth rate.

Environmental policy ($\tilde{P} < 0$ with $a_Y = 0$)

Environmental policy reduces the long-run real return and hence harms the growth rate. How sensitive the real return and growth are with respect to economy-wide pollution depends on the cross-shares. In particular, the real return (and hence growth) is rather sensitive to environmental policy if the (cross) share of pollution in the production of capital, $(1-\alpha)$, is large relative to the (cross) share of capital in the production of knowledge, β. Intuitively, in that case, pollution plays an important role in overall production because it accounts for a large share in the production of both capital and knowledge (i.e. both $1-\alpha$ and $1-\beta$ are large). Environmental policy does not affect the real return if pollution does not enter the production of capital (i.e. $\alpha = 1$). In this case, growth in final goods output can be sustained without the need for knowledge inputs from the knowledge-producing sector, or in other words: the 'core' of the model consists only of the capital-producing sector. Since pollution does not affect the 'core', it leaves both the real return and growth unaffected (see Rebelo (1991)). The 'core' of the model is limited to the knowledge-producing sector if capital does not impact the production of effective pollution (i.e. $\beta = 0$), because then growth in final goods output can be sustained without growth in capital K (provided that $\alpha < 1$). In that case, the elasticity of the real return with respect to the economy-wide level of pollution is (at its maximum of) unity.

Environment as production factor ($\tilde{P} < 0$ with $a_Y > 0$)

Environmental policy may facilitate long-run growth if a better environmental quality N enhances the productivity of the consumption-goods sector and the environment is thus not only a consumption good but also a production factor. The condition for an improved growth performance is (from (5.3) and (5.4)):

$$\beta \cdot a_Y > (1-\alpha)\left(\frac{E_N N}{E_P P}\right) \tag{5.6}$$

Growth improves if a change in pollution affects strongly the absorption capacity of nature ($-E_P$ large), if the negative feedback of a higher stock of natural capital on the absorption capacity is small ($-E_N$ small) and if the positive impact of a higher environmental quality on productivity is large (i.e. a_Y large). Furthermore, the share of capital in the knowledge-producing sector, β, should be large relative to the share of pollution in the capital-producing sector, $(1-\alpha)$. Intuitively, the positive impact of environmental quality on productivity A_Y should dominate its adverse effect on the absorption capacity of the environment. Furthermore, capital K and environmental quality N should be relatively important in production (i.e. β and a_Y should be large) while pollution should feature only small production shares (i.e. $1-\alpha$ and $1-\beta$ should be small). Hence, the positive effect on the production sector of more abundant (natural and produced) capital dominates the adverse effect of lower pollution.

5.3 The sectoral distribution of economic activity

The expression for the share of effective pollution allocated to the capital-producing sector, v, consists of two terms, one representing the impact of *relative* productivity shocks and the other the effect of *aggregate* productivity shocks (see Appendix B):

$$\tilde{v}\left(\frac{v}{1-v}\right) = -\beta(1-\sigma_H)\left(\frac{\tilde{A}_Y - \tilde{A}_H - \tilde{P}}{1-\alpha+\beta}\right) - \left(\frac{\theta}{r-\theta}\right)\tilde{r} \tag{5.7}$$

Relative productivity shocks ($\tilde{A}_Y - \tilde{A}_H$)

The first term at the right-hand side of (5.7) represents the impact of changes in the relative productivity of the two production processes. The sector that becomes relatively less productive attracts a larger share of economy-wide pollution as long as the substitution elasticity in the knowledge-producing sector is smaller than unity (i.e. $\sigma_H < 1$).

Intuitively, a relative productivity shock exerts both a *scale* and a *substitution* effect. The scale effect implies that the more productive sector requires less production factors to supply the same output. At the same time, however, production becomes more intensive in the factor produced by the more productive sector (see Subsection 5.1). This substitution effect boosts output in the more productive sector (relative to production in the other sector). Accordingly, relative demand for production factors in the more productive sector expands. The importance of this latter (substitution) effect depends on the substitution possibilities between the two factors. If the substitution elasticity is smaller than one, the scale effect dominates the substitution effect and a larger share of pollution is thus allocated to the less productive sector. The following expression for the fraction of economy-wide capital allocated to the consumption-good sector, u, reveals that similar forces are operating on this fraction (see Appendix B):

$$\tilde{u}\left(\frac{v}{1-u}\right) = [(\sigma_Y - \sigma_H)(v-\beta) - \beta(1-\sigma_Y)]\left(\frac{\tilde{A}_Y - \tilde{A}_H - \tilde{P}}{1-\alpha+\beta}\right) - \left(\frac{\theta}{r-\theta}\right)\tilde{r} \tag{5.8}$$

In particular, if the substitution elasticity in the capital-producing sector, σ_Y, is small, capital moves toward the less productive sector.

Aggregate productivity shocks ($\tilde{r}$)

The aggregate productivity term in (5.7) and (5.8) can be written as (from $r = (g/\sigma) + \theta$)):

$$\left(\frac{\theta}{r-\theta}\right)\tilde{r} = \sigma\left(\frac{\theta}{g}\right)\tilde{r} \tag{5.9}$$

If aggregate productivity and hence the real return rises, activity declines in the consumption goods sector as long as the rate of time preference, θ, and the intertemporal substitution elasticity, σ, are positive (substitute (5.9) into (5.7) and (5.8)). Intuitively, a higher return boosts the growth rate if intertemporal substitution in consumption is feasible. Higher growth pulls activity away from the consumption-goods sector and toward the pure 'investment' sector (i.e. the knowledge-creating sector). The aggregate productivity effect becomes more powerful in affecting the intersectoral allocation if elastic saving behavior (i.e. a large intertemporal substitution elasticity σ) implies a substantial response of growth to changes in aggregate productivity.

Environmental policy ($\tilde{P} < 0$ with $a_Y = 0$)

Less pollution (i.e. $\tilde{P} < 0$) enters the expressions for $\tilde{v}$ and $\tilde{u}$ in the same way as an adverse productivity shock in the knowledge-creating sector (i.e. $\tilde{A}_H < 0$). The reason is that the long-run supply of *effective* pollution is reduced in the same way by less pollution as by a less productive learning sector. How environmental policy affects the intersectoral allocation of production factors thus depends on the impact of the relative and aggregate productivity effects. On the one hand, by reducing the relative supply of effective pollution (i.e. the relative productivity effect), environmental policy expands the knowledge-creating sector, especially if substitution in production is difficult (i.e. σ_Y and σ_H are small, see the first terms at the right-hand sides of (5.7) and (5.8)). On the other hand, less pollution harms aggregate productivity and thus growth, thereby moving activity into the consumption-good sector (see the last terms at the right-hand sides of (5.7) and (5.8)). This latter impact of environmental policy becomes more important if the intertemporal substitution elasticity is large. If both intertemporal substitution in consumption and substitution in production is difficult, the first effect dominates and environmental policy thus expands the sector producing pollution-saving technology. [7] Intuitively, to substitute for pollution, the economy invests mainly in knowledge instead of either investing in physical capital (, which would happen if substitution in production would be easy) or consuming (, which would happen if intertemporal substitution of consumption would be easy).

Section 3 established that pollution is 'essential' in production if substitution elasticities do not exceed unity. Hence, environmental policy typically boosts the sector producing pollution-saving technological progress unless the intertemporal substitution elasticity is large. In the case of Cobb-Douglas production functions (i.e. $\sigma_Y = \sigma_H = 1$), however, substitution between capital and pollution is relatively easy and the economy would thus substitute quite a lot of capital for pollution. Indeed, activity would move to the capital-producing sector if both the rate of time preference and the intertemporal substitution elasticity are positive. Intuitively, the relative productivity effect would leave the intersectoral allocation unaffected (i.e. the first terms on the right-hand sides of (5.7) and (5.8) would be zero). At the same time, the intertemporal substitution effect on account of lower aggregate productivity would move activity to the consumption-good sector.

The environment as production factor ($\tilde{P} < 0$ with $a_Y > 0$)

If the quality of the environment raises the productivity of the capital-producing sector, environmental policy is even more likely to raise activity in the knowledge-producing sector. The reason is that the relative productivity effect becomes stronger while the aggregate productivity effect becomes weaker and may even change sign. It becomes more attractive to employ production factors in developing pollution-saving technologies

[7] The share of capital allocated to the knowledge-creating sector may fall if substitution in the capital-producing sector is easy and, at the same time, substitution in the knowledge-producing sector is difficult. In that case, the capital-producing sector absorbs a relatively large share of the decline in pollution (see expression (5.1)). Only in that sector can capital substitute for pollution. Hence, capital moves to the capital-producing sector.

because investing becomes more attractive relative to consuming (intertemporal substitution) and because effective pollution becomes even more scarce relative to capital.

5.4 The knowledge-intensity of economy-wide production

The effect on the overall knowledge-intensity of production, K/h, can be written as the sum of three terms (see Appendix B):

$$\tilde{K} - \tilde{h} = \sigma_u \left(\frac{\tilde{A}_Y - \tilde{A}_H - \tilde{P}}{1 - \alpha + \beta} \right)$$

$$+ \left[\frac{g(\beta - \alpha)}{\alpha r + g(\beta - \alpha)} \right] \left\{ \beta(1 - \sigma_H) \left(\frac{\tilde{A}_Y - \tilde{A}_H - \tilde{P}}{1 - \alpha + \beta} \right) + \left(\frac{\theta}{r - \theta} \right) \tilde{r} \right\}$$

$$+ \tilde{P} \tag{5.10}$$

The first term represents substitution between capital and effective pollution on the sectoral level as a result of relative productivity shocks. It corresponds to the effects on sectoral factor-intensities considered in Subsection 5.1. In particular, production becomes more intensive in the factor that becomes 'easier' to produce as a result of the relative productivity shock. The economy-wide importance of factor substitution on the sectoral level depends on the ease of substitution as reflected in the 'aggregate' substitution elasticity σ_u defined as the weighted average of the two sectoral substitution elasticities:

$$\sigma_u = u\sigma_Y + (1 - u)\sigma_H \tag{5.11}$$

Hence, the first term vanishes if substitution on the micro level is not feasible (i.e. $\sigma_Y = \sigma_H = 0$).

The second term stands for substitution between capital and knowledge as a result of different sectoral factor-intensities. This is called 'macro-economic' substitution as opposed to substitution at the sectoral level considered in Subsection 5.1. In particular, production on the macro level becomes more capital intensive if economic activity moves toward the sector that is relatively capital intensive. If the knowledge-creating sector is relatively capital intensive (i.e. $\beta > \alpha$), for example, the aggregate capital-knowledge ratio (K/h) rises if production factors move to that sector.[8] As discussed in Subsection 5.3, the knowledge-creating sector expands if this sector becomes relatively less productive (as long as $\sigma_H < 1$) or aggregate productivity rises (as long as θ and σ are positive).

The last term at the right-hand side of (5.10) reflects substitution between, on the one hand, pollution and, on the other hand, knowledge about pollution-saving technology. As pollution and knowledge are substitutes, lower pollution corresponds to more knowledge-intensive production.

Environmental policy ($\tilde{P} < 0$ with $a_Y = 0$)

In the absence of substitution on micro and macro levels (i.e. both $\sigma_u = 0$ and $\alpha = \beta$), environmental policy yields more knowledge-intensive production as knowledge substitutes for pollution. Substitution on the micro level mitigates this shift. If substitution between capital and effective pollution is feasible (i.e. $\sigma_u > 0$, see the first term on the right-hand side of (5.10)), the economy substitutes not only knowledge but also capital for pollution. If factor-intensities are identical in both sectors (i.e. $\alpha = \beta$), substitution to knowledge dominates substitution to capital as long as the substitution elasticity in the knowledge-creating sector is smaller than one. Hence, environmental policy generally raises the knowledge-intensity of production as measured by the capital-knowledge ratio. In the Cobb-Douglas case, the two substitution effects exactly offset each other and the capital-knowledge ratio is not affected.

If the knowledge-producing sector is most capital intensive (i.e. $\beta > \alpha$, see the second term on the right-hand side of (5.10)), environmental policy typically implies macro substitution towards capital. With low intertemporal and interfactor substitution (i.e. σ, σ_H and σ_Y are small), environmental policy boosts activity in the knowledge-creating sector (see Subsection 5.3). If this sector is relatively capital intensive, the sectoral re-

[8] Note that (the negative of) the term between accolades equals the expression for $\tilde{v}(v/(1-v))$ on the right-hand side of equation (5.7).

allocation of activity raises the demand for capital. This reduces the positive impact of environmental policy on the knowledge-intensity of production. Intuitively, capital is an important input in the accumulation of knowledge.

Accordingly, if the knowledge-creating sector is relatively capital-intensive (i.e. $\beta > \alpha$), macro-, and not only micro-, substitution tends to mitigate the effect of environmental policy on the knowledge-intensity of production. Only if the intertemporal elasticity is large may macro substitution strengthen the trend toward more knowledge-intensive production. The reason is that, if intertemporal substitution is easy, the lower return implies a shift of activity towards the consumption goods sector. Since this sector is pollution-intensive, this raises the demand for knowledge about pollution-saving technology.

To determine the overall effect of environmental policy if $\alpha \neq \beta$, we write (3.10) as:

$$\tilde{K} - \tilde{h} = \left(1 - \frac{\beta - \alpha}{1 - \alpha + \beta}\right)(\tilde{A}_Y - \tilde{A}_H) + \left(\frac{\beta - \alpha}{1 - \alpha + \beta}\right)\tilde{P}$$

$$-(1 - \sigma_u)\left[\frac{\alpha r + (1 - \beta)g(\beta - \alpha)}{\alpha r + g(\beta - \alpha)}\right]\left(\frac{\tilde{A}_Y - \tilde{A}_H - \tilde{P}}{1 - \alpha + \beta}\right)$$

$$+\left[\frac{g(\beta - \alpha)}{\alpha r + g(\beta - \alpha)}\right]\left[\left(\frac{\theta}{r - \theta}\right)\tilde{r} + \beta u(\sigma_Y - \sigma_H)\left(\frac{\tilde{A}_Y - \tilde{A}_H - \tilde{P}}{1 - \alpha + \beta}\right)\right] \tag{5.12}$$

Production becomes more knowledge-intensive as long as the knowledge-creating sector is relatively more capital intensive (i.e. $\beta > \alpha$) and the substitution elasticities are equal and do not exceed one (i.e. $\sigma_u \leq 1$). Even with relatively easy substitution in the case of Cobb-Douglas production functions, environmental policy reduces the knowledge-intensity of production only if the creation of knowledge is relatively pollution intensive (i.e. $1 - \beta > 1 - \alpha$). In this latter case, environmental policy inhibits the creation of knowledge because pollution in an important input in the production of knowledge. Furthermore, lower growth boosts the consumption goods sector. Also this effect makes production less knowledge intensive if the consumption-goods sector is relatively capital intensive.

The environment as a production factor ($\tilde{P} < 0$ with $a_Y > 0$)

If environmental policy raises the productivity of the capital-producing sector, environmental policy may well cause production to become more capital rather than knowledge intensive. The intuition is that environmental policy expands the supply of capital by raising the productivity of the capital-producing sector. If micro substitution is easy, substitution from effective pollution to capital may well offset the substitution of knowledge for pollution.

If the knowledge-producing sector is most capital-intensive (i.e. $\beta > \alpha$), macro substitution may also work in the direction of more capital intensive production if environmental policy enhances the productivity of the capital-producing sector. In particular, higher overall productivity stimulates saving, thereby reducing activity in the consumption-goods sector. However, lower pollution inhibits the supply of capital if the capital-producing sector is relatively pollution intensive (see expression (5.12)). This mitigates the positive effect of a more productive capital-producing sector on the capital-knowledge ratio.

5.5 Consumption to capital ratio

The long-run solution for the consumption to capital ratio, C/K, is given by (see Appendix C):

$$\tilde{C} - \tilde{K} = (1-\sigma)\left(\frac{r}{r-g}\right)\tilde{r} + (1-\alpha)\left[\frac{r}{r+g(\beta-\alpha)}\right]\left(\frac{\tilde{A}_Y - \tilde{A}_H - \tilde{P}}{1-\alpha+\beta}\right)$$

$$-(1-\alpha)\sigma_u\left[\frac{r}{r+g(\beta-\alpha)}\right]\left(\frac{\tilde{A}_Y - \tilde{A}_H - \tilde{P}}{1-\alpha+\beta}\right)$$

$$-\left[\frac{g(\beta-\alpha)}{r+g(\beta-\alpha)}\right]\left[\frac{(1-\alpha)r}{\alpha r+g(\beta-\alpha)}\right]\left\{\beta(1-\sigma_H)\left(\frac{\tilde{A}_Y - \tilde{A}_H - \tilde{P}}{1-\alpha+\beta}\right) + \left(\frac{\theta}{r-\theta}\right)\tilde{r}\right\} \quad (5.13)$$

The steady-state expression for the consumption-knowledge ratio, C/h, is found by combining (5.10) and (5.13):

$$\tilde{C}-\tilde{h}=(1-\sigma)\left(\frac{r}{r-g}\right)\tilde{r}+(1-\alpha)\left[\frac{r}{r+g(\beta-\alpha)}\right]\left(\frac{\tilde{A}_Y-\tilde{A}_H-\tilde{P}}{1-\alpha+\beta}\right)$$
$$+\sigma_u\left[\frac{\alpha r+g(\beta-\alpha)}{r+g(\beta-\alpha)}\right]\left(\frac{\tilde{A}_Y-\tilde{A}_H-\tilde{P}}{1-\alpha+\beta}\right)$$
$$+\left[\frac{g(\beta-\alpha)}{r+g(\beta-\alpha)}\right]\left\{\beta(1-\sigma_H)\left(\frac{\tilde{A}_Y-\tilde{A}_H-\tilde{P}}{1-\alpha+\beta}\right)+\left(\frac{\theta}{r-\theta}\right)\tilde{r}\right\}$$
$$+\tilde{P} \tag{5.14}$$

Aggregate productivity shocks ($\tilde{r}$)

The first term in expressions (5.13) and (5.14) stands for intertemporal substitution of consumption due to movements in the overall real rate of return. A higher real return yields both an income and a substitution effect. The income effect boosts the consumption to capital ratio. The substitution effect, in contrast, raises saving and investment relative to consumption, thereby reducing the long-run ratio of consumption to capital. The income effect dominates the intertemporal substitution effect if the intertemporal substitution elasticity, σ, is smaller than one.

Relative productivity shocks ($\tilde{P} < 0$ with $\tilde{A}_Y - \tilde{A}_H$)

The impact of changes in the relative productivity of the consumption goods sector is represented by the second term in the expressions above. In particular, if the consumption goods sector becomes more productive compared to the knowledge-producing sector, consumption becomes more abundant relative to capital. Conversely, assets (i.e. physical capital and knowledge) rise relative to consumption if the relative productivity of the knowledge-creating sector (i.e. the 'investment' sector) improves.

In contrast to the first two terms, the other terms in expression (5.13) for the consumption-capital ratio have a different sign than the corresponding terms in expression (5.14) for the consumption-knowledge ratio. The reason is that these latter terms correspond to the impact of productivity shocks on the capital-knowledge ratio, K/h. In particular, the third term reflects substitution between capital and knowledge on the sectoral ('micro-economic') level. If the capital-producing sector becomes relatively more productive, sectors will substitute capital for effective pollution and the capital-effective pollution ratio thus increases. With more capital-intensive production, the consumption-capital ratio declines and the consumption-knowledge ratio rises.

The fourth term captures the effect of 'macro-economic' substitution between capital and effective pollution on account of different sectoral factor intensities. If the knowledge-creating sector is most capital intensive, overall production becomes more capital intensive if activity moves to this sector (see Subsection 5.4).

The final term featuring economy-wide pollution enters only expression (3.13) for the ratio of consumption to knowledge. This term stands for the substitution between pollution and knowledge. Hence, the consumption to knowledge ratio rises with pollution.

Environmental policy ($\tilde{P} < 0$ with $a_Y = 0$)

Lower pollution generally reduces the consumption to knowledge ratio. Intuitively, the adverse income effect associated with lower growth reduces consumption relative to assets. At the same time, knowledge becomes a more important asset than capital as the economy substitutes knowledge rather than capital for pollution. The fall in the ratio of consumption to knowledge is particularly large if the intertemporal substitution elasticity σ and the substitution elasticities in production, σ_Y and σ_H, are small and the capital-producing sector is relatively pollution intensive (i.e. $\beta > \alpha$ and thus $1 - \alpha > 1 - \beta$, which implies that the cross elasticities $1 - \alpha$ and β are quite large). Low intertemporal substitution implies that the income effect dominates the substitution effect of a lower rate of return and thus prevents the lower return from raising consumption relative to assets. At the same time, substitution of capital for pollution is quite difficult because of two reasons. First, the low substitution elasticities σ_Y and σ_H inhibit substitution on micro level. Moreover, lower pollution exerts a larger negative impact on the supply of capital than on that of knowledge because pollution is a relatively important input into the production of capital (i.e. $1 - \alpha > 1 - \beta$).

Indeed, environmental policy can raise the consumption-knowledge ratio only if the intertemporal substitution exceeds unity, the knowledge sector is relatively pollution intensive (i.e. $\beta < \alpha$), and substitution on the micro level is close to unity. In that case, the large intertemporal substitution elasticity causes consumption to rise relative to assets. At the same time, capital rather than knowledge is substituted for pollution due to the large elasticities on the micro level and a substantial adverse effect of lower pollution on the production of knowledge.

The environment as a production factor ($\tilde{P} < 0$ with $a_Y > 0$)

If the quality of the environment features not only in utility but also in production, the consumption to knowledge ratio falls less and may even rise. Three factors strengthen consumption relative to knowledge. First, the positive income effect associated with a higher overall level of productivity raises consumption relative to assets, at least if the intertemporal substitution elasticity is smaller than one (so that the income effect dominates the substitution effect). Second, the consumption goods sector becomes more productive. Hence, consumption rises relative to assets. Finally, the composition of assets changes towards more capital and less knowledge because the capital-producing sector becomes more productive. Indeed, if the positive effect of a better environmental quality on production is strong enough, the capital to knowledge ratio may rise rather than fall (see Subsection 5.4) – especially if the substitution elasticities in production are large.

5.6 The tax on pollution

In a decentralized economy firms equate the marginal productivity of pollution to the pollution tax τ_P according to (4.1). This yields the following long-run impact on the price for effective pollution (in terms of final goods), τ_P/h, (see Appendix D):

$$\tilde{\tau}_P - \tilde{h} = \left(\frac{\tilde{A}_Y - \tilde{A}_H - \tilde{P}}{1 - \alpha + \beta} \right) + \tilde{r} \tag{5.15}$$

The price for effective pollution rises if aggregate productivity increases (i.e. $\tilde{r} > 0$) or if a relative productivity shock causes the capital-producing sector to become more productive compared to the knowledge-sector (i.e. $\tilde{A}_Y - \tilde{A}_H > 0$). Intuitively, the marginal productivity of pollution increases if either the economy as a whole becomes more productive (i.e. $\tilde{r} > 0$) or if a more productive final goods sector (i.e. $\tilde{A}_Y - \tilde{A}_H > 0$) implies that capital becomes more abundant relative to effective pollution.

Environmental policy ($\tilde{P} < 0$) raises the price of effective pollution. This effect is strengthened if the environment enters as a production factor in the final-goods sector (i.e. $a_Y > 0$ and thus $\tilde{A}_Y > 0$). The intuition is that a lower level of economy-wide pollution renders effective pollution more valuable. This is especially so if a lower level of pollution raises the supply of final goods by making the final-good sector more productive.

5.7 The price of knowledge

The price of knowledge (in terms of final goods), q_h, is found by log-linearizing (2.6) and substituting (5.1):

$$\tilde{q}_h = \frac{\tilde{A}_Y - \tilde{A}_H}{1 - \alpha + \beta} + \left(\frac{\beta - \alpha}{1 - \alpha + \beta}\right)\tilde{P} \tag{5.16}$$

Knowledge becomes scarcer and therefore more expensive, relative to physical capital if the capital-producing sector becomes more productive compared to the knowledge sector (i.e. $\tilde{A}_Y - \tilde{A}_H > 0$). If N does not enter production (i.e. $a_Y = 0$), environmental policy ($\tilde{P} < 0$) reduces the price of knowledge as long as the capital-producing sector is relatively pollution intensive (i.e. $1 - \alpha > 1 - \beta$ and thus $\beta > \alpha$). Intuitively, a lower level of pollution harms production most in the pollution-intensive sector. Since this sector produces capital, capital becomes scarcer relative to knowledge. Therefore, the value of knowledge in terms of capital declines.

If the quality of the environment facilitates production ($a_Y > 0$), the price of knowledge may rise as environmental policy boosts the supply of final goods by raising the productivity of the final goods sector.

5.8 Public spending

The ratio $q_h H/Y$ reflects the relative importance of the public sector in a decentralized market economy. The impact on this ratio is given by (see Appendix D):

$$\tilde{q}_h + \tilde{H} - \tilde{Y} = \left[\alpha(1-\sigma_Y) + \beta\left(\frac{1-v}{v}\right)(1-\sigma_H)\right]\left(\frac{\tilde{A}_Y - \tilde{A}_H - \tilde{P}}{1-\alpha+\beta}\right)$$

$$+\frac{1}{v}\left(\frac{\theta}{r-\theta}\right)\tilde{r} \qquad (5.17)$$

A relative productivity shock favoring the private sector (i.e. $\tilde{A}_Y - \tilde{A}_H > 0$) boosts the public spending ratio (as long as $\sigma_Y, \sigma_H < 1$). Intuitively public spending becomes more expensive and more rival production factors move toward the less productive sector (see also Subsection 5.3). A positive aggregate productivity shock ($\tilde{r} > 0$) also boosts public spending because it favors the pure investment sector.

If the environment is not productive ($a_Y = 0$), environmental policy typically makes public spending relatively more important. Only if intertemporal substitution and substitution in production are relatively easy may the public spending ratio fall. In that case, the economy substitutes privately produced capital as well as private consumption for pollution rather than publicly-produced knowledge.

Public spending is even more likely to rise if the environment enters production. The reason is that a more productive final good sector makes private spending even less expensive (relative to public spending). Moreover, a higher level of aggregate productivity is reflected in a higher real return, which favors investment over private consumption.

6 Optimal environmental policy

If the level of pollution is chosen optimally, the following arbitrage condition must hold in the steady state (see 2.9):

$$\frac{L\,(U_N/U_c) + (\partial Y/\partial N)}{h\,(\partial Y/\partial Z_Y)} = (r-g) + (-E_N(N,P)), \qquad (6.1)$$

It is optimal to invest in natural capital by reducing the level of pollution up to the point where the marginal benefits of a higher quality of the environment (LHS) equal the marginal costs (RHS). The benefits consist of two components: first, higher utility because of the amenity of the stock of environmental capital and second, higher productivity (if N is a factor of production). Both components are scaled by the decline in output through the shift to a less pollution-intensive production process (denominator on LHS). The first element of the costs at the RHS represents the capital cost, which amounts to the return on the two alternative types of investment (r), corrected for 'capital gains' on natural capital; with knowledge and physical capital growing at rate g, the relative price of natural capital, which is fixed in supply on a balanced growth path, increases at rate g. As natural capital becomes scarcer and therefore its marginal value grows steadily, investment in natural capital is relatively attractive (the required current return is lower than that on other assets). The second cost element at the RHS is 'depreciation' of natural capital, $\delta_N = -E_N(N, P) > 0$. A higher level of natural capital reduces the absorption capacity of the environment (see Section 2).

Environmental policy can be driven by a shift in preferences that raises *ceteris paribus* the marginal utility of environmental services. If N is not a factor of production ($\partial Y/\partial N = dA_Y/dN = 0$), log-linearization of (6.1) yields:

$$(r - g + \delta_N)\left[\tilde{\phi} + \pi\left(\frac{E_p P}{E_N N}\right)\tilde{P} + \tilde{C} - \tilde{h} - \left(\tilde{A}_Y + \alpha\frac{\tilde{A}_Y - \tilde{A}_H - \tilde{P}}{1 - \alpha + \beta}\right)\right] =$$

$$r(1 - \sigma)\tilde{r} - [E_{NN}(-E_P/E_N) + E_{NP}]P\tilde{P} \qquad (6.2)$$

where $\tilde{\phi}$ stands for an exogenous relative change in the marginal rate of substitution between N and C and π represents the elasticity of U_N/U_c with respect to N. A 'green' preference shift ($\tilde{\phi} > 0$) typically implies a decline in the optimal level of pollution. The increased marginal utility of N is an incentive to invest more in environmental quality which requires a reduction in pollution. Following the increase in N, the marginal benefits of N fall while the marginal costs of higher N and lower P rise until the arbitrage condition (6.2) is re-established. There is little room for combating pollution if these feed-backs of higher N on benefits and costs are strong.

The second term in square brackets represents the decline in marginal utility of natural capital in response to a higher stock of natural capital associated with lower pollution. The marginal benefits fall quickly if marginal utility of environmental quality is diminishing rapidly with N (i.e. π large). If the absorption capacity of the environment is not very sensitive to changes in the environment ($-E_N$ small), but sensitive to changes in $P(-E_p$ large), N rises substantially with lower P. Hence, marginal utility of N declines rapidly.

The third and fourth terms in square brackets represents the trade-off between consumption, pollution-saving knowledge and environmental quality. The more the consumption to knowledge ratio declines in response to a reduction in pollution (see equation (5.14)), the faster the marginal utility of consumption and the marginal productivity of pollution rises (through a fall in C and a rise in h respectively). If substitution between effective pollution and capital is difficult, the capital-knowledge ratio declines substantially (see Subsection 5.4). In that case, the marginal productivity of pollution $h\ \partial Y/\partial P_Y$ rises rapidly. Hence, further cuts in pollution become more costly. The two terms in round brackets on the left-hand side of (6.1) reflect other impacts on the marginal productivity of pollution. The lower the level of pollution, the higher its marginal value as a factor of production and thus the more costly further cutting pollution becomes.

The first term on the RHS represents changes in the growth corrected cost of capital. A decline in pollution reduces the rate of return (see expression (5.4)). Accordingly, the marginal cost of environmental investment falls and thus provides new incentives to reduce pollution, unless the rate of intertemporal substitution exceeds one (i.e. $\sigma > 1$). In this latter case, the real return (i.e. the return corrected for capital gains) rises. The reason is that the rate of growth, which yields the capital gains on natural capital, declines by more than the rate of return. However, the – realistic – case that $\sigma < 1$ does not provide a strong stimulus to cut pollution since it is at least partly counterbalanced by a decline in the consumption-knowledge ratio ($\tilde{C} - \tilde{h}$) due to a lower rate of return (see first term at the right-hand side of (5.14)). This latter effect reduces the net benefits of environmental policy. According to the last term on the RHS of (6.2), the marginal cost of environmental policy is typically rising with reductions in pollution if the expression in square brackets is positive (which is assumed in Figure 1). The reason is that natural capital depreciates faster at higher levels of N (i.e. $E_{NN} < 0$) and this compensates the rise in absorbtion capacity due to lower pollution (i.e. $E_{NP} < 0$).

To summarize, a higher priority for the environment cuts pollution substantially if U_N declines and depreciation rises slowly with N (i.e. π and E_{NN} small), compared to N pollution exerts a weak impact on the accumulation of natural capital (i.e. E_P/E_N small), the marginal productivity of pollution rises slowly with P (α small), and substitution between capital and effective pollution is easy (σ_Y large and the cross-elasticities are large so that production does not become more knowledge intensive very rapidly).

Environment as production factor ($a_Y > 0$)

The positive link between the quality of the environment and productivity in the consumption goods sector provides additional incentives for environmental policy. However, if this link is subject to strongly diminishing returns (i.e. $A''_Y N/A'_Y << 0$), the impact of a preference shift on the optimal level of pollution is mitigated because a higher level of N sharply reduces the marginal contribution of natural capital to production. Moreover, if natural capital plays an important role in production (A_Y large), a higher level of N raises the marginal productivity of other production factors, including pollution. Hence, the costs of environmental policy rise with higher levels of N. Furthermore, if substitution in production is difficult, lower pollution raises the knowledge intensity of production. This raises the marginal productivity of pollution $h\partial Y/\partial P_Y$, thereby increasing the costs of environmental policy. If the productivity term (i.e. the second term on the LHS of 6.1) dominates the utility term (i.e. the first term), the effects of the productivity term determine the impact of a given preference shock on the quality of the environment. In particular, N rises substantially if substitution in production is easy (i.e. σ_Y and σ_H large).

With natural capital directly productive, the effect on the growth-corrected rate of return will be changed. In particular, a lower level of pollution produces a smaller decline of the rate of return and may even raise the rate of return (see expression (5.6)). If $\sigma < 1$, the higher return makes environmental policy less attractive and thus reduces the impact of a green preference shock.

The productivity effects of N also change the effects on the utility component of the current returns (i.e. the first term at the LHS of (6.1)). As discussed in Subsection 5.5, a lower level of pollution tends to produce a smaller fall in C/h and may actually raise this ratio if environmental capital is productive. This strengthens the effect of a preference shock on steady state environmental quality. However, a higher stock of natural capital raises the cost of cutting pollution by raising the marginal productivity of pollution $\partial Y / \partial P_Y$. This effect mitigates the impact of a preference shock.

7 Conclusions

This paper has developed an endogenous growth model that incorporates pollution-saving technological change and, at the same time, includes the natural environment as a renewable resource. The model simultaneously determines the time paths for three types of assets: renewable resources, physical capital, and knowledge. The accumulation of these three asset stocks is affected by the endogenous flows of, respectively, pollution, saving, and inputs into the R&D sector. The ratio of physical capital to knowledge constitutes a measure for the direction of technological progress. In particular, if this ratio declines, technological progress becomes more pollution saving.

Section 3 derived the conditions under which sustainable balanced growth is not only feasible but also optimal. In such a situation, consumption and man-made inputs (knowledge and physical capital) are growing, while the flow of pollution and the stock of natural capital remain constant. This implies that the shadow price of natural resources rises over time, thereby encouraging substitution away from environmental services toward consumption and the input of man-made factors of production. Constant environmental quality is feasible and optimal only if these substitution effects offset exactly the income effects due to the growth in productivity. Hence, balanced optimal growth requires unitary elasticities of substitution between environmental services and consumption in the utility function and between environmental services and man-made factors of production in the production functions. Furthermore, it must be excluded that technologies with decreasing (increasing) returns to scale in the man-made factors become dominant in the economy as a whole, since this would imply ever-falling (increasing) rates of growth.

How the government should intervene to achieve optimal growth was investigated in Section 4. Private agents do not internalize the adverse effect of pollution on the aggregate stock of natural capital; a tax on pollution is therefore necessary. This tax should rise at the growth rate of pollution-saving knowledge, since the development of new technology raises the productivity of polluting inputs and provides *ceteris paribus* an incentive to increase pollution. Pollution-saving knowledge is a public good and should thus be provided by the government. We found that the government should earmark only part of the revenues from the pollution tax for investing in pollution-saving knowledge. Intuitively, the tax revenues measure the return on pollution-saving knowledge. As a kind of golden rule, the government should 'consume' part of this return.

Section 5 explored the link between, on the one hand, long-run growth and, on the other hand, a more ambitious environmental policy, which is associated with a smaller aggregate flow of pollution and, in a market economy, a higher pollution tax. Section 6 showed that the experiment performed in Section 5 can be interpreted as a shift in preferences towards more concern for the environment. Section 5 distinguished between the case in which the non-extractive use of the natural environment enters only the utility function and the case in which it enters also the production function for final goods. Environmental policy reduces in the extractive use of the environment. If environmental quality does not enter production, this implies that the productivities of both kinds of man-made capital decline and that the rates of return and growth fall. The adverse impact on long-run growth is especially serious if pollution plays an important role in the final good sector, while at the same time physical capital accounts for only a small production share in the learning sector. The growth impact of environmental policy is changed if environmental quality enhances production in the final goods sector. In particular, long-run growth may benefit from environmental policy if lower pollution exerts a strong positive long-run impact on the sustainable stock of natural capital while natural and physical capital account for large production shares.

We explored also the impact of environmental policy on the bias of technological change, the size of the public sector, and the role of various elasticities of substitution. Technology becomes more pollution saving (indicated by a smaller capital to knowledge ratio), the more difficult substitution is between capital and polluting inputs and the smaller is the productive role of the environment. However, if substitution is easy and the environment is directly productive in the capital goods sector, the supply of capital is boosted and the economy relies more on physical capital and less on knowledge to replace pollution. Increased environmental concern typically raises activity in the learning sector, thereby expanding the relative importance of public spending. This effect is particularly large if substitution between capital and knowledge is difficult and if the environment enhances the productivity of the capital-producing sector.

An obvious extension of this paper is to study the transitional dynamics of the model. The short-term effects of environmental policy on growth are likely to be negative. In early stages, the reduction in polluting inputs dominates (cf. the case that $a_Y = 0$ analyzed in this paper), while only in later stages the stock of environmental services will have risen enough to boost growth (cf. $a_Y > 0$). Another valuable extension involves the incorporation of public spending on abatement. In that case, distortionary taxes may be required to finance public spending if lump-sum taxes are not available.

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Appendix A

Eliminating q_h from (2.6) and (2.7), we find:

$$\frac{\partial Y/\partial K_Y}{\partial Y/\partial Z_Y} = \frac{\partial H/\partial K_H}{\partial H/\partial Z_H} \tag{A.1}$$

The initial steady-state version of (A.1) is:

$$\frac{\alpha}{(1-\alpha)}\frac{v}{u} = \frac{\beta}{(1-\beta)}\frac{(1-v)}{(1-u)} \tag{A.2}$$

On a balanced growth path (i.e. $\dot{q}_h = 0$), the optimal choice between investing in capital and technological knowledge is characterized by (see 2.9)):

$$\frac{\partial Y}{\partial K_Y} = P\frac{\partial H}{\partial Z_H} = r \tag{A.3}$$

where we have assumed $\delta_H = \delta_K = 0$. Defining $C/K \equiv x$ and $\dot{K}/K \equiv g_K$ so that $Y/K = x + g_K$, and noting that in the steady state $\dot{h}/h = g_h = g_K = g$, we can write (A.3) as:

$$\frac{\alpha}{u}(g+x) = \frac{(1-\beta)}{(1-v)}g = r \tag{A.4}$$

Solving for v, we find (3.9). Substituting (3.9) into (A.2) to eliminate v and solving for u, we arrive at (3.8).

Log-linearizing (A.1) and (A.3), we find

$$\frac{1}{\sigma_Y}(\tilde{Z}_Y - \tilde{K}_Y) = \frac{1}{\sigma_H}(\tilde{Z}_H - \tilde{K}_H) \tag{A.5}$$

$$\tilde{A}_Y + \frac{(1-\alpha)}{\sigma_Y}(\tilde{Z}_Y - \tilde{K}_Y) = \tilde{A}_H + \tilde{P} - \frac{\beta}{\sigma_H}(\tilde{Z}_H - \tilde{K}_H) = \tilde{r} \tag{A.6}$$

These two equations yield the solutions for the sectoral factor intensities (5.1). Substituting these solutions in (A.6), we find expression (5.4) for the effect on the rate of return $\tilde{r}$.

Appendix B

The growth rate of knowledge, $g_H = \dot{h}/h$, is found from (3.5):

$$g_H = \frac{A_H G(K_H, Z_H)}{Z_H} \left(\frac{Z_H}{h}\right) \tag{B.1}$$

Substituting $Z_H = (1-v)hP$ and log-linearizing, we arrive at:

$$\tilde{g}_H = \tilde{A}_H + \tilde{P} + \beta(\tilde{K}_H - \tilde{Z}_H) - \frac{v}{1-v}\tilde{v} \tag{B.2}$$

Substitution of the steady-state solutions for $\tilde{K}_H - \tilde{Z}_H$ (from (5.1)) and using $\tilde{g}_H = \tilde{g}$ yields:

$$\frac{v}{1-v}\tilde{v} = \tilde{A}_H + \tilde{P} - \tilde{r} + \beta\sigma_H \left(\frac{\tilde{A}_Y - \tilde{A}_H - \tilde{P}}{1-\alpha+\beta}\right) + \tilde{r} - \tilde{g} \tag{B.3}$$

Substituting (5.3) and (5.4), we find (5.7).

Log-linearization of the definitions $v \equiv Z_Y/hP$ and $u \equiv K_Y/K$ yields:

$$\tilde{v} = \tilde{Z}_Y - \tilde{P} - \tilde{h} \tag{B.4}$$

$$\tilde{u} = \tilde{K}_Y - \tilde{K} \tag{B.5}$$

Combining (B.4) and (B.5) and defining $z \equiv K/h$ as the capital to knowledge ratio, we find:

$$(\tilde{K}_Y - \tilde{Z}_Y) = (\tilde{z} - \tilde{P}) + \tilde{u} - \tilde{v} \tag{B.6}$$

We know that $(1-v)hP = Z_H$ and $(1-u)K = K_H$. Log-linearization yields:

$$-\frac{v}{(1-v)}\tilde{v} + \tilde{h} + \tilde{P} = \tilde{Z}_H \tag{B.7}$$

$$-\frac{u}{(1-u)}\tilde{u} + \tilde{K} = \tilde{K}_H \tag{B.8}$$

Subtracting (B.7) from (B.8), we arrive at:

$$\tilde{K}_H - \tilde{Z}_H = (\tilde{z} - \tilde{P}) + \frac{v}{(1-v)}\tilde{v} - \frac{u}{(1-u)}\tilde{u} \tag{B.9}$$

Substituting the steady-state solutions for $(\tilde{K}_Y - \tilde{Z}_Y)$ and $(\tilde{K}_H - \tilde{Z}_H)$ from (5.1) and for $\tilde{v}$ from (5.7), we can solve for the long-run solutions for $\tilde{u}$ and $\tilde{z} - \tilde{P}$.

In particular, subtraction of (B.6) from (B.9) and multiplying the result by v yields:

$$v\left\{(\tilde{K}_H - \tilde{Z}_H) - (\tilde{K}_Y - \tilde{Z}_Y)\right\} = -\frac{v}{(1-u)}\tilde{u} + \frac{v}{(1-v)}\tilde{v} \tag{B.10}$$

Substituting (5.1) and (5.7) into (B.10) yields expression (5.8) for $\tilde{u}$.

In order to find the steady-state solution for $\tilde{z}$, we write (B.9) as:

$$\tilde{z} = \tilde{P} + (\tilde{K}_H - \tilde{Z}_H) + \left(\frac{u}{1-u}\right)\tilde{u} - \left(\frac{u}{1-v}\right)\tilde{v} - \left(\frac{v-u}{v}\right)\left(\frac{v}{1-v}\right)\tilde{v} \tag{B.11}$$

Substitution of (B.10) (after multiplying with u/v) into (B.11) yields

$$\tilde{z} = \tilde{P} + (1-u)(\tilde{K}_H - \tilde{Z}_H) + u(\tilde{K}_Y - \tilde{Z}_Y) - \left(\frac{v-u}{v}\right)\left(\frac{v}{1-v}\right)\tilde{v} \tag{B.12}$$

We find (5.10) by substituting (5.1) and (5.7) and using (from (3.8) and (3.9)):

$$\frac{v-u}{v} = \frac{g(\beta-\alpha)}{\alpha r + g(\beta - \alpha)} \tag{B.13}$$

Appendix C

The growth rate of the capital stock, $g_K = \dot{K}/K$, is found by substituting (3.4) into (2.4)

$$g_K = \frac{A_Y F(K_Y, P_Y)}{K_Y} \frac{K_Y}{K} - \frac{C}{K} \tag{C.1}$$

where we have used $\delta_K = 0$. Log-linearization of (C.1) yields:

$$g\tilde{g}_K = (g + x)\left[\tilde{A}_Y + (1-\alpha)(\tilde{P}_Y - \tilde{K}_Y) + \tilde{u}\right] - x\tilde{x} \tag{C.2}$$

where $x \equiv C/K$. Substitution of $\tilde{g}_K = \tilde{g}$, (5.1), (5.3), and (5.8) yields:

$$x\tilde{x} = (g + x)\left\{\tilde{r} + [(1-\sigma_Y)(1-\alpha) + (1-u)(\sigma_Y - \sigma_H) + (1-u)\frac{\beta}{v}(\sigma_H - 1)]\right.$$

$$\left.\left(\frac{\tilde{A}_Y - \tilde{A}_H - \tilde{P}}{1-\alpha+\beta}\right) - \frac{1-u}{v}\left(\frac{\theta}{r-\theta}\right)\tilde{r}\right\} - g\left[1 + \frac{\theta}{r-\theta}\right]\tilde{r} \tag{C.3}$$

where we have used (5.4) to eliminate $\tilde{A}_Y$. We can write (C.3) as

$$\tilde{x} = \frac{g+x}{x}\left[(1-\sigma_Y)(u-\alpha) + (1-\sigma_H)\frac{v-\beta}{v}(1-u)\right]\left(\frac{\tilde{A}_Y - \tilde{A}_H - \tilde{P}}{1-\alpha+\beta}\right) +$$

$$\left[1 - \left(\frac{\theta}{r-\theta}\right)\left(\frac{g}{x} + \frac{(g+x)}{x}\frac{(1-u)}{v}\right)\right]\tilde{r} \tag{C.4}$$

The first term in squared brackets at the right-hand side of (C.4) can be written as

$$(1-\sigma_Y)(u-\alpha) + (1-\sigma_H)\left(\frac{v-\beta}{v}\right)(1-u)$$

$$= (1-\sigma_u)\frac{u-\alpha}{u} + (1-\sigma_H)\left[\frac{v-\beta}{v} - \frac{u-\alpha}{u}\right](1-u) \tag{C.5}$$

where σ_u is defined in (5.11).

We express $g + x$ in terms of g and r by using (A.4) and (3.8):

$$(g + x) = \frac{u}{\alpha} r = r \frac{[r - g + \beta g]}{[\alpha(r - g) + \beta g]} \tag{C.6}$$

Using (C.6), we arrive at x in the initial steady state:

$$x = \frac{(r - g)[r + g(\beta - \alpha)]}{\alpha(r - g) + \beta g} \tag{C.7}$$

We also find from (3.8):

$$\frac{u - \alpha}{u} = (1 - \alpha)\left[\frac{r - g}{r - g + \beta g}\right] \tag{C.8}$$

and

$$1 - u = (1 - \alpha)\left[\frac{\beta g}{\alpha(r - g) + \beta g}\right] \tag{C.9}$$

Using (3.9), we arrive at:

$$\frac{v - \beta}{v} = (1 - \beta)\left[\frac{r - g}{r - g + \beta g}\right] \tag{C.10}$$

We can now use (C.6)-(C.10) to write the first term in squared brackets at the right-hand side of (C.4) as

$$(1 - \alpha)\left[\frac{r}{r + g(\beta - \alpha)}\right]\left\{(1 - \sigma_u) - \left[\frac{g(\beta - \alpha)}{\alpha r + g(\beta - \alpha)}\right]\beta(1 - \sigma_H)\right\} \tag{C.11}$$

We can simplify the term in front of $\tilde{r}$ at the right-hand side of (C.4) by using (derived from (C.6), (C.7), (C.9) and (3.9))

$$\frac{g}{x} + \left(\frac{g + x}{x}\right)\left(\frac{1 - u}{v}\right) = \frac{g}{r - g} + \frac{g(\beta - \alpha)(1 - \alpha)r}{[\alpha r + g(\beta - \alpha)][r + g(\beta - \alpha)]} \tag{C.12}$$

and (derived from (5.2)):

$$\frac{\theta}{r - \theta} = \frac{r}{g}(\sigma - 1) + \frac{r - g}{g} \tag{C.13}$$

Substituting (C.12) and (C.13) to rewrite the term in front of $\tilde{r}$ in (C.4), we find:

$$1-\left(\frac{\theta}{r-\theta}\right)\left[\frac{g}{x}+\left(\frac{g+x}{x}\right)\left(\frac{1-u}{v}\right)\right]=$$

$$(1-\sigma)\left(\frac{r}{r-g}\right)-\left[\frac{g(\beta-\alpha)}{r+g(\beta-\alpha)}\right]\left[\frac{(1-\alpha)r}{\alpha r+g(\beta-\alpha)}\right]\left(\frac{\theta}{r-\theta}\right) \quad (C.14)$$

Substitution of (C.11) and (C.14) into (C.4) yields (5.13).

Appendix D

Log-linearization of (2.1) yields:

$$\dot{\tilde{N}} = E_N\tilde{N}+\left(\frac{E_P P}{N}\right)\tilde{P} \quad (D.1)$$

In the steady state, $\dot{\tilde{N}}=0$. Hence, the long-run relationship between the flow of pollution and the stock of natural capital is given by

$$\tilde{N}=-\left(\frac{E_P P}{E_N N}\right)\tilde{P} \quad (D.2)$$

Log-linearization of E_N yields:

$$\tilde{E}_N=\left(\frac{E_{NN}N}{E_N}\right)\tilde{N}+\left(\frac{E_{NP}P}{E_N}\right)\tilde{P}. \quad (D.3)$$

From the utility function $U=U(c,N)$, we find:

$$\tilde{U}_N-\tilde{U}_c=\tilde{\phi}+\left(\frac{\partial(U_N/U_c)}{\partial c}\right)\left(\frac{c}{U_N/U_c}\right)\tilde{c}+\left(\frac{\partial(U_N/U_c)}{\partial N}\right)\left(\frac{N}{U_N/U_c}\right)\tilde{N} \quad (D.4)$$

where $\tilde{\phi}$ is an exogenous preference shock. In Section 3 we showed that the elasticity of

U_N/U_c with respect to consumption should equal unity to guarantee balanced growth. If we write $-\pi$ for the second elasticity in (D.4) and substitute (D.2) and $\tilde{c} = \tilde{C} - \tilde{L}$, we arrive at:

$$\tilde{U}_N - \tilde{U}_c = \tilde{\phi} + (\tilde{C} - \tilde{L}) + \pi \left(\frac{E_P P}{E_N N}\right) \tilde{P} \tag{D.5}$$

From production functions (3.4) and (3.5) and equation (5.1) we find:

$$(\partial Y \tilde{/} \partial Z_Y) = \tilde{A}_Y + \frac{\alpha}{\sigma_Y}(\tilde{K}_Y - \tilde{P}_Y) = \tilde{A}_Y + \alpha \left(\frac{\tilde{A}_Y - \tilde{A}_H - \tilde{P}}{1 - \alpha + \beta}\right) \tag{D.6}$$

$$(\partial H \tilde{/} \partial Z_H) = \tilde{A}_H + \frac{\beta}{\sigma_H}\left(\tilde{K}_H - \tilde{P}_H\right) = \tilde{A}_H + \beta \left(\frac{\tilde{A}_Y - \tilde{A}_H - \tilde{P}}{1 - \alpha + \beta}\right) \tag{D.7}$$

Combining (4.1), (5.4), and (D.6), we find (5.15). (5.16) is found by log-linearizing (2.6) and substituting (D.6) and (D.7).

The arbitrage-condition (6.1) in the steady state can be written as:

$$\frac{LU_N/U_c}{h(\partial Y/\partial Z_Y)} + a_Y \left(\frac{v}{1-\alpha}\right) \frac{P}{N} = r - g + \delta_N \tag{D.8}$$

Log-linearizing of (6.1) and substituting (D.8), we find:

$$\left[r - g + \delta_N - a_Y \left(\frac{v}{1-\alpha}\right) \frac{P}{N}\right] (\tilde{L} + \tilde{U}_N - \tilde{U}_c) + \alpha_Y \left(\frac{v}{1-\alpha}\right) \frac{P}{N} \cdot \left(\frac{\partial \tilde{Y}}{\partial N}\right) =$$

$$r\tilde{r} - g\tilde{g} - E_N \tilde{E}_N \tag{D.9}$$

Substituting (5.3), (D.2), (D.3), (D.5) and (D.6) into (D.9) yields (6.2) in the case that $a_Y = 0$.

Finally, we arrive at (5.17) by using

$$\tilde{H} = \tilde{A}_H + \tilde{Z}_H + \beta(\tilde{K}_H - \tilde{Z}_H) \tag{D.10}$$

and

$$\tilde{Y} = \tilde{A}_Y + \tilde{Z}_Y + \alpha(\tilde{K}_Y - \tilde{Z}_Y) \tag{D.11}$$

and substituting (B.4), (B.7) and (5.1), and then employing (5.7) to eliminate $\tilde{v}$ and (5.16) to rewrite $\tilde{q}_h$.

Table 1:

The long-run impacts of productivity shocks and environmental policy[1].

	Productivity shocks		Environmental policy ($\tilde{P} < 0$)	
	Relative shocks ($\tilde{A}_Y - \tilde{A}_H > 0$)	Aggregate shocks $\tilde{r} > 0$	Environment not productive $a_Y = 0$	Environment productive $a_Y > 0$
$\tilde{K}_Y - \tilde{Z}_Y$	+	0	+	++
$\tilde{K}_H - \tilde{Z}_H$	+	0	+	++
$\tilde{g}$	0	+	−	−/+
$\tilde{v}$	−[2]	−	−[3]	−
$\tilde{u}$	−[4]	−	−[5]	−
$\tilde{K} - \tilde{h}$	+[6]	+[7]	−[8]	−/+
$\tilde{C} - \tilde{K}$	+	+[9]	−/+	−/+
$\tilde{C} - \tilde{h}$	+	+	−	−/+
$\tilde{r}_P - \tilde{h}$	+	+	+	++
$\tilde{q}_h$	+	0	−[7]	−/+

Footnotes

1) The substitution elasticities σ_Y and σ_H and the intertemporal elasticity σ are assumed not to exceed 1.

2) 0 if $\sigma_H = 1$.

3) Unless σ and σ_H are large.

4) Unless σ_Y is large compared to σ_H and, at the same time, $r >> g$ (so that $v >> \beta$).

5) Unless σ and σ_Y are large.

6) Unless $\beta < \alpha$ and, at the same time, σ_Y and σ_H are small.

7) Unless $\beta < \alpha$.

8) Unless $\beta < \alpha$ and, at the same time, σ_Y and σ_H are large.

9) Unless $\beta > \alpha$ and, at the same time, σ is large.

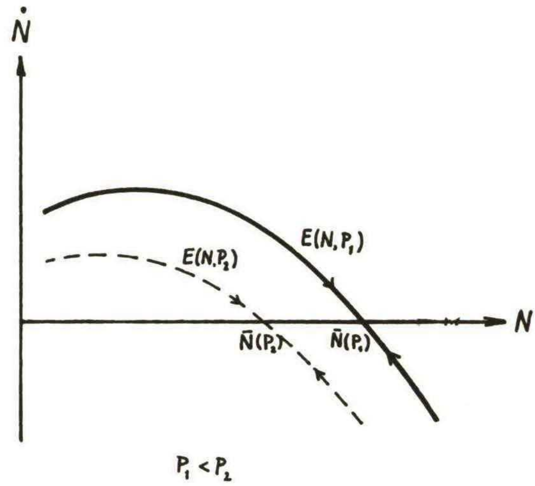

Figure 1 : the regeneration function for the environment

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