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**POLLUTION ABATEMENT AND
LONG-TERM GROWTH**

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POLLUTION ABATEMENT AND LONG-TERM GROWTH*

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Abstract To examine the question whether sustained growth and environmental quality are compatible, a macroeconomic model is developed where the environment is essential for production and welfare and where the growth rate is an endogenously determined variable. Pollution is an inevitable side-product of economic activity. It can be reduced by spending a fraction of total output on abatement activities.

It is examined first under what conditions sustainable growth is feasible and when this is optimal. The influence of increased environmental care on the growth rate is traced. Increased environmental care affects long-term output growth through three channels: crowding out of investment, productivity improvements, and intertemporal substitution of consumption. Externalities arise because the *economy-wide level* of pollution affects negatively the productivity of production factors and welfare.

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1. Introduction

Recent models of macroeconomic growth endogenize the long-run growth rate and explain how technological possibilities, preferences, market distortions and institutions affect economic growth (e.g. Romer 1986, 1990, Lucas 1988, Grossman and Helpman 1991). Sustained growth is possible because physical limits to growth are continually offset by the accumulation of capital and knowledge, which requires a certain allocation of resources towards growth generating activities. This literature on "endogenous growth" has arisen from the limited applicability of older models of (optimal) growth where the long-run growth rate is exogenous (e.g. Cass 1965, Koopmans 1967). These models are unsuited to explain real world phenomena like persistent growth differentials among countries and the recent productivity slowdown. Another shortcoming of the Cass-Koopmans optimal growth framework is that it abstracts from externalities, public goods, uncertainty and asymmetric information.

Among the externalities that are important in the process of growth are those associated with pollution and environmental issues. Growth in economic activity may increase pollution and environmental degradation, so that growth is less desirable when taking into account this amenity value of the environment. Moreover, the quality of the environment affects the productivity of production factors and consequently the rate of growth, e.g. by affecting the health of workers, the quality of natural inputs, and the rate of capital depreciation. Since aggregate pollution matters and individual agents ignore the effect of their own actions on aggregate pollution levels, externalities arise. It is useful to separate the *environmental amenity externality* from the *productivity externality* (cf. Pezzey 1989). E.g. Forster (1973) and Van der Ploeg and Withagen (1991) consider the former externality by adding pollution as a disutility in the preference ordering of economic agents. The productivity externality is incorporated in e.g. Nordhaus (1982), where pollution enters the production function.

The relation between long-run growth and environmental issues has been the subject of public discussion for long. The first report for the Club of Rome (Meadows 1972) received a lot of attention. It used a complex dynamic simulation model to illustrate the limits to growth due to exhaustibility of natural resources. The update version of the report (Meadows 1992) stresses the dangers of rapid degradation of renewable resources. The rather pessimistic view in these reports and from other environmentalists has been criticized by more optimistic economists stressing the opportunities for substitution between natural and man-made inputs, technological change and market incentives (see Nordhaus 1992). A more empirical contribution to the debate provides the World Development Report (1992) that points at the relation between the level of economic development and various kinds of environmental degradation. Other empirical studies focus typically on environmental problems due to energy use and on the transitional growth effects within a neoclassical framework (e.g. Jorgenson and Wilcoxon 1990).

Surprisingly, the interaction between long-term growth and the environment is only rarely tackled in analytical models. Incorporating environmental issues in neoclassical growth models (e.g. Mäler 1975) is less suited to study this issue, since it assumes that the long-term growth rate is exogenously given. The issue requires environmental aspects to be incorporated in the endogenous growth framework. A formal model is important to precisize concepts and to check the consistency of alledged feedback mechanisms. It may clarify the debate between "pessimists" and "optimists" by specifying what kind of conditions are needed for certain scenarios to arise.

This paper applies endogenous growth theory to deal with the question whether sustained growth and environmental quality are compatible. A growth model is presented where pollution is an inevitable side-product of economic activity. Pollution can be reduced by spending a fraction of total output on abatement activities. Increased environmental care affects long-term output growth through three channels: (1) the productivity effect: environmental care improves the quality of natural and other factors of production which may enhance growth, (2) the crowding out effect: the more resources are spent on abatement, the less are left for growth generating activities, (3) the intertemporal substitution effect: the crowding out effect may be offset by reducing consumptive spending. Our model suggests that if the productivity of abatement is relatively high, if the preference for the environment is relatively low and if the society is patient enough, an increase in environmental care is associated with an increase in growth. In the market economy where abatement levels are too low due to environmental externalities, introducing the appropriate tax (a pollution tax or the combination of a tax on economic activity and a subsidy on abatement) will increase the growth rate under these conditions.

In Section 2, we examine under what conditions balanced and sustainable growth is feasible, while Section 3 shows when this is optimal. Section 4 characterizes growth in the social optimal. To trace the effects of increased environmental care on the growth rate, two experiments are considered. Section 5 deals with the effects of an increase in the preference for a clean environment on the optimal growth rate. In Section 5, the focus is on the internalizing of externalities associated with pollution in the decentralized economy.

2. Production structure and conditions for balanced growth

Physical capital (K) is the only (direct) factor of production. It should be interpreted as a broad measure of capital, including for instance also human capital and energy or natural resources saving technical knowledge. The natural environment is an indirect factor of production. A higher quality of the environment, which is directly related to the level of net pollution per unit of air,

soil *etc.* (P),¹ positively affects the productivity of direct factors of production, e.g. by reducing physical depreciation, enhancing the quality of natural inputs, or the health of workers. Output (Y) is allocated over consumption (C), pollution abatement (A) and investment ($\dot{K}$). The shares of output devoted to consumption and abatement are given by s_c and s_a respectively. Net pollution (P) is positively related to capital, to capture the polluting consequences of economic activity², and negatively to abatement.

$$Y = Y(P, K) \quad Y_K > 0, Y_P < 0,^3 \quad (1)$$

$$\dot{K} = Y - C - A = (1 - s_c - s_a)Y \quad (2)$$

$$P = P(A, K) \quad P_A < 0, P_K > 0. \quad (3)$$

Dividing (2) by K and substituting (1) and (3) gives the solution for the growth rate or the Harrod Domar condition:

$$g = \frac{\dot{K}}{K} = (1 - s_a - s_c) \cdot \frac{Y(P(A, K), K)}{K}. \quad (4)$$

It can be examined now under which conditions sustained growth is feasible given production technology, given the relation between pollution and economic activity and given spending on consumption and environmental care (abatement). Especially we are interested in the familiar concept of *balanced growth*. It is defined as the situation in which all variables grow at a constant (possibly zero) rate of growth and in which the relative allocation of resources over spending categories is constant (i.e. s_a and s_c are constant). The latter implies that A , C , $\dot{K}$ and Y grow at the same rate. A constant rate of growth in the capital stock requires that K and Y grow at the same rate. Hence, the output capital ratio must remain constant when K and A grow at a common constant rate. This restricts the production function to constant returns with respect to capital, taken into account the effects of capital accumulation on pollution. Accumulation of capital reduces the average product of capital through pollution ($Y_P P_K dK$) and this must be offset exactly

¹ Alternatively, the stock of accumulated pollution rather than the current flow of pollution may determine the quality of the environment. In Appendix B, we show that this assumption does not affect qualitatively the conclusions for the steady state.

² In the literature [e.g. Forster (1973) and Van der Ploeg and Withagen (1991)] often output (Y) is the source of pollution rather than capital. These assumptions are equivalent if capital (K) is the only direct factor of production. A more complex pollution function could incorporate consumption generating municipal wastes (as in Luptacik and Schubert 1982), and population density occupying space and hindering the regeneration processes in nature.

³ A subscripted function symbol denotes the partial derivative ($F_x = \partial F / \partial x$), a dot denotes the time derivative ($\dot{x} \equiv \partial x / \partial t$).

by the increase in spending on pollution abatement in line with capital accumulation ($Y_P P_A dA$) and scale returns to capital ($(Y_K - Y/K)dK$). Formally, we need constant returns to scale (CRS) with respect to the growing factors of production:

$$\chi\lambda = \chi\gamma + (\beta - 1) \quad \Leftrightarrow \quad \beta - \chi(\lambda - \gamma) = 1 \quad (\text{CRS}) \quad (5)$$

$$\text{where } \chi \equiv -\frac{\partial Y / \partial P}{Y/P}, \quad \beta \equiv \frac{\partial Y / \partial K}{Y/K}, \quad \gamma \equiv -\frac{\partial P / \partial A}{P/A}, \quad \lambda \equiv \frac{\partial P / \partial K}{P/K}$$

Evidently, in order to sustain a balanced growth path, condition (5) must remain valid over time once the economy grows along a balanced path. If the production function belongs to the class of CES functions, the elasticities β and χ depend on the capital pollution ratio (K/P) except in the case that the elasticity of substitution equals unity. Since K/P changes along a balanced growth path, a non-unitary elasticity of substitution cannot imply balanced growth as defined above since: either (i) the CRS-condition will be valid some point in time but then inevitable be violated because β and χ change over time, or (ii) the CRS-condition is only reached asymptotically, i.e. balanced growth occurs only at the infinite future. Hence we focus on a Cobb-Douglas production function $Y(K, P)$ where β and χ are parameters.⁴ Following the same reasoning, $\lambda - \gamma$ has to be constant along a balanced growth path. This is guaranteed if the pollution function features a constant elasticity of substitution, so that both elasticities are either a function of the abatement capital ratio A/K (but this ratio is constant), or are parameters.

Under these assumptions of constant returns to capital and constant elasticities, the output capital ratio is a function of the abatement ratio only, $Y/K = y(s_a)$, and the growth rate is endogenously determined by s_a and s_c through the Harrod-Domar or Goods Market Equilibrium (GME) equation:

$$g = (1 - s_c - s_a) y(s_a) \quad (\text{GME}) \quad (6)$$

⁴ If we would widen our scope to asymptotically balanced growth, non-unitary (but constant) elasticities of substitution need not be ruled out. Consider the case that K/P rises over time, i.e. the case where the natural production factor is scarce [this is the relevant case if $\lambda < \gamma$, see ESG-condition (7)]. (i) If the elasticity of substitution between P and K exceeds 1, the production elasticity of the fastest growing factor will rise over time. Hence, $\beta(K/P) = \beta(\infty) = \zeta_\gamma$ and $\chi(K/P) = \chi(\infty) = 0$, if the production function is homogeneous of degree ζ_γ . The CRS-condition requires a constant return to scale production function ($\zeta_\gamma = 1$). However, this case is less interesting for the subject of the paper, since it implies that the natural environment is not essential for production. (ii) Alternatively, if the elasticity of substitution falls short of 1, the production elasticity of the fastest growing factor will fall over time. Hence, $-\chi(\infty) = \zeta_\gamma$ and $\beta(\infty) = 0$. Only the improvement of the environment accounts for growth. The CRS-condition requires $\chi(\infty)(\gamma - \lambda) = 1$. However, given condition (7), this implies $\gamma\chi \geq 1$ so that the production $Y(K, P(A, K))$ is not concave in A and that the second order conditions of the optimization problem are not satisfied.

It can be derived that the elasticity of the output capital ratio equals $y's_a/y = \gamma\chi/(1-\gamma\chi) > 0$.⁵

All stylised growth models need to impose restrictions on production functions to guarantee balanced growth. If one introduces additional assumptions on the production structure as here by introducing a relation between production and pollution, additional restrictions are needed. The restriction of constant returns to growing factors in the aggregate production structure is well known from e.g. Rebelo (1991).⁶

There are no *a priori* reasons why the conditions for balanced growth hold. In the model above, growth will tend to zero if the growth in abatement spending is not enough to choke off the polluting consequences of industrial activity ($\chi\gamma + \beta - I < \chi\lambda$): pollution levels rise over time and productivity levels fall. This can only temporarily be compensated by raising the abatement propensity s_a , because abatement spending cannot exceed total income ($s_a < I$). Taking pollution effects into account, there are diminishing returns to capital and therefore growth cannot be sustained in the long run. The gloomy picture arises that by the nature of technology growth and sustainable development are inevitably incompatible. In the opposite case, growth will rise infinitely which can be slowed down by reducing s_a : abatement (and production) technology is so successful (i.e. there are increasing returns to capital: $\chi\gamma - \chi\lambda + \beta > I$) that a lower and lower share of output is to be spent on abatement to keep growth or pollution constant.

In the former situation, the issue of long-term growth and environmental issues cannot be addressed, while in the latter situation, the environment puts no limits on growth. Hence, it is most interesting to confine the remainder of this paper on the situation of balanced growth. Whether this situation is realistic is of course an empirical question. There is, however, neither *a priori* reason nor empirical evidence to reject it. As argued by Weissmahr (1991), in the last 15,000 years, man managed to reorganize his way of living and producing such that the use of the ecological system (measured as global energy use expressed in mega-watt-hours) rose at a factor 10,000. In terms of our stylized model, this means that there are constant returns with respect to the reproducible production factors K and A , so that long-term balanced growth is feasible.

Besides the influence of pollution on the economic subsystem (production), also the influence of pollution on the ecological subsystem should be examined. Since the regeneration or absorption capacity of nature is limited, there is an upper limit on the flow of net pollution that can be maintained without irreversibly destroying eco-systems (cf. Barbier and Markandya, 1990). This upper limit, or critical load (to be denoted by $\bar{P}$), imposes an *ecological viability constraint* on

⁵ Concavity of the production function requires that $\gamma\chi < I$.

⁶ The formal structure of our model is comparable to Barro (1990), where the focus is on infrastructure instead of abatement. We, however, assume that the environment (and therefore indirectly abatement) enters both the production function and the utility function, consider additional (environmental) constraints, study other forms of taxation and do not consider abatement as a *pure* public good.

balanced growth paths. Only equilibria for which $P \leq \bar{P}$ are ecologically sustainable. Balanced growth can only continue forever if the growth path starts with a pollution level not exceeding the critical load and if pollution does not rise along the balanced growth path so that the critical load is not exceeded on future dates. Since in a situation of balanced growth pollution changes at rate $\dot{P}/P = (\lambda - \gamma)g$, the restriction

$$\lambda \leq \gamma. \quad (ESG) \quad (7)$$

is necessary for ecologically sustainable growth (ESG).⁷

3. Preferences and optimal allocation

The next issue is whether sustainable (balanced) growth is optimal. Social welfare depends not only on per capita consumption of material goods but possibly also on the quality of the environment, here measured by the aggregate level of pollution:

$$W = \int_0^{\infty} U(c, P) e^{-\theta t} dt \quad U_c > 0, U_P \leq 0. \quad (8)$$

Per capita consumption is denoted by c . By abstracting from population growth and normalizing the population size to one, $c = C$. In this section we consider the *social optimum* where welfare is maximized by choosing the optimal level of abatement (A) and consumption (C) subject to the production function (1), pollution function (3) and goods market equilibrium (2). The conditions for an optimum are:

$$U_P P_A + U_C Y_P P_A = U_C = \theta_I, \quad (9)$$

$$U_P P_K + \theta_I (Y_P P_K + Y_K) = \delta \theta_I - \dot{\theta}_I, \quad (10)$$

where θ_I is the costate variable. The first equation states that the marginal contributions of A and C to welfare should be equalised every point in time. Using the definitions of the elasticities, this can be rewritten as:

$$s_a = \gamma(\phi s_c + \chi), \quad \phi = -U_P P / U_C c. \quad (11)$$

⁷ Note that if strict inequality applies in (7), the balanced growth path tends to the "ecological paradise" (cf. Michel 1993) in the infinite future where pollution approximates zero.

The intuition behind this equation is that abatement activities are attractive ($s_a > 0$) when pollution is a disutility ($\phi > 0$) and/or when pollution affects productivity ($\chi > 0$), provided that abatement is effective in reducing pollution ($\gamma > 0$). If $\phi = 0$, s_a is independent of s_c and equal to $\gamma\chi$. Optimal abatement spending is then determined only by the production/pollution structure and not affected by preferences. If $\phi > 0$, this dichotomy is no longer present. The abatement level can not be chosen independently from the consumption level because there is a trade-off between consumption and pollution levels through instantaneous utility $U(c, P)$. Abatement is proportional to consumption: the larger the relative importance of environment in utility (i.e. the larger ϕ), the larger is environmental spending relative to consumption spending (s_a/s_c).

The second condition (10) determines the dynamic optimality of the allocation. Using $U_c(c, P) = \theta_t$ and condition (11), one finds:

$$\left(\beta - \frac{\lambda}{\gamma} s_a \right) \frac{Y}{K} = \delta + \left(\frac{-U_{cc}c}{U_c} \right) \frac{\dot{c}}{c} + \left(\frac{-U_{cP}P}{U_c} \right) \frac{\dot{P}}{P}. \quad (12)$$

This can be interpreted as a variation on the well-known Ramsey rule. The LHS is the marginal rate of return in consumption terms. It takes into account that a fraction of the gross marginal product of capital (i.e. $\beta Y/K$) must be spent on abatement costs ($(\lambda/\gamma)s_a Y/K$) to maintain the productivity of capital. Note that if λ/γ is large, capital is relatively heavily polluting and abatement relatively ineffective, which means that the marginal abatement cost associated to capital is large. The LHS is called the social rate of return (r^s). The Ramsey rule equates the social rate of return to the required rate of return, which is on the RHS. It depends on the growth rate g for two reasons. First, as usual, the faster growth in consumption is, the faster marginal utility falls and the less tomorrow's returns to savings are valued: a larger rate of growth implies less consumption smoothing for which a premium over the pure rate of time preference is asked, equal to the second term on the RHS. Secondly, growth is associated with changes in pollution (if $\lambda \neq \gamma$) which is a second source for changes in the marginal utility of consumption (provided that $U_{cP} \neq 0$). It results in a premium in the required rate of return, equal to the last term on the RHS.

Conditions (11) and (12) show that restrictions on the utility function are needed to guarantee that growth is balanced in the optimum (cf. King, Plosser and Rebelo, 1988). From (11) it is clear that s_a and s_c will only be constant if ϕ remains constant while C and P grow at a possibly different rate. This means that the elasticity of substitution between consumption and environmental quality in the utility function must be unity.⁸ Otherwise, growth in income would make it optimal to substitute consumption spending for abatement spending or *vice versa*. Since ecologically sustainable growth requires that pollution does not grow in the steady state, the

⁸ By definition, ϕ evolves over time according to $\dot{\phi}/\phi = (1 - 1/\sigma_u)(\dot{P}/P - \dot{c}/c)$, where σ_u is the elasticity of substitution between c and P in utility.

consumption to pollution ratio rises and the contribution of pollution to social welfare declines (ϕ declines). However, this invokes substitution effects because the disutility of pollution will rise (a clean environment becomes more and more scarce relative to consumption). If environmental quality and consumption are poor substitutes, the latter effect will dominate, ϕ rises and abatement spending (s_a) is enlarged.

From equation (12), it is clear that the elasticity of marginal utility, both with respect to consumption and with respect to pollution (i.e. the terms in brackets on the RHS), should be constant if c and P grow at a possibly different rate. Otherwise, constant growth rates of pollution and consumption are associated with a growth rate of marginal utility of consumption that varies over time and, consequently, a varying required rate of return. This would cause the social rate of return to vary as well, so that s_a and Y/K cannot be constant.

Appendix A derives the specification of the instantaneous utility function that guarantees balanced growth, which reads:

$$U(c, P) = \begin{cases} \frac{(cP^{-\phi})^{1-\rho_c}}{1-\rho_c} & \text{for } \rho_c \neq 1 \\ \ln c - \phi \ln P & \text{for } \rho_c = 1 \end{cases} \quad (13)$$

Note that in the case that the environment has no amenity value ($\phi=0$), equation (13) reduces to the standard CRRA utility function, where ρ_c is the coefficient of risk aversion.

In a situation of balanced growth, (12) can be written as:

$$g = \frac{[\beta - (\lambda/\gamma)s_a] y(s_a) - \delta}{\rho}, \quad (DD\text{-curve}) \quad (14)$$

where $\rho \equiv \rho_c + (\rho_c - 1)(\gamma - \lambda)\phi$ indicates how the (steady state) required rate of return is related to the (steady state) growth rate g . Equivalently, $1/\rho$ can be interpreted as the (steady state) intertemporal rate of substitution.

4. Abatement and growth in the social optimum

Equations (6), (11), and (14) provide the framework to study some elementary effects of increased environmental care on optimal growth. From equation (6), *GME*, it is clear that a rise in the fraction of income spent to abatement (s_a) has ceteris paribus two opposite effects. On the one hand, it reduces the fraction of income spent on investment ($1 - s_a - s_c$) and therefore reduces growth. On the other hand, pollution will be lower and the average productivity of capital ratio (y) is enhanced which implies higher growth. The former effect can be labeled the *crowding out effect*

and the latter the *productivity effect*. The former, negative, effect can be (partly) offset by lowering the propensity to consume (s_c), which we will call the *intertemporal substitution effect*: by reducing current consumption, capital is accumulated at a higher rate and future consumption is higher.

Equation (6) represents the *feasible* growth rate for given s_a and s_c . It is straightforward to derive that for given s_c the growth rate dictated by goods market equilibrium and production/pollution technology is at its maximum if $s_a = \gamma\chi(1-s_c)$: raising s_a from this level will depress growth because crowding out effects will dominate productivity effects, while lowering s_a will depress growth because a decline in productivity dominates the crowding in of resources available for investment. Equivalently, $s_a = \gamma\chi$ maximizes $(1-s_a)y(s_a) = (Y-A)/K$ which is the net average return to capital in the sense that abatement costs (A/K) are subtracted from gross return Y/K .

While (6) represents the feasible growth rate, (11) and (14) determine the *desired* levels of g , s_a and s_c . First consider the desired level of abatement activities each moment in time. From equation (11) we see that if pollution does not matter in utility ($\phi=0$), $s_a = \gamma\chi$ is the optimal level. In an optimum, the net, or after-abatement-allowances, return to capital is maximized first and then this maximum return is allocated over consumption and investment according to intertemporal preferences. A lower level ($s_a < \gamma\chi$) can never be an optimum, because a rise in abatement spending is always welfare improving since it raises the average net return to capital. Thus, starting from $s_a < \gamma\chi$, increasing abatement provides a higher productivity, from which higher current consumption, higher growth in future consumption and/or lower levels of pollution can be financed. If $\phi > 0$, abatement is not only initiated to exploit productivity effects but also to reduce the disutility of pollution, so s_a will be higher than $\gamma\chi$.

Whether pollution enters utility or not, in both cases, optimal abatement spending s_a will exceed $\gamma\chi(1-s_c)$ so that, given the optimal consumption abatement ratio as expressed in (11), an increase in abatement spending (s_a) will reduce growth because crowding out effects dominate productivity effects. The downward sloping curve SS in Figure 1 represents this negative relationship between s_a and g . Its mathematical form is found by eliminating s_c between (6) and (11):

$$g = \left(\frac{\chi + \phi}{\phi} - \frac{1 + \phi\gamma}{\phi\gamma} s_a \right) y(s_a). \quad (SS\text{-curve}) \quad (15)$$

The SS curve portrays the *feasible* combinations of growth rate g and abatement spending s_a if the consumption to abatement ratio is set optimally. Which of these combinations is optimal depends on intertemporal preferences, represented by equation (14).

Equation (14) provides the dynamic part of the model depicted as curve DD . It portrays the desired rate of growth for each s_a which depends directly on the marginal return from savings. An increase in s_a has two effects. First it raises the marginal return to savings through the

productivity effect on y , which provides an incentive to postpone consumption and raise growth. Secondly, the larger s_a , the more of the returns to savings (to capital) must be spent on abatement activity: abatement allowances become a larger cost component which reduces the incentive to grow. For large values of s_a , the latter effect dominates, the marginal return decreases with s_a , and DD slopes downward so that the curve is hill-shaped. Simple manipulation reveals that the two effects balance at $s_a = \beta \cdot \gamma \chi \cdot \gamma / \lambda$. If the gross returns to capital are large (β large), if productivity effects are strong ($\gamma \chi$ large), or if abatement is relatively effective and capital relatively clean (γ / λ large), then productivity effects dominate over a large range for s_a . In this range, increasing the abatement propensity fosters the marginal rate of return to savings and a higher rate of growth is desired (DD slopes upward). The society is willing to reduce consumption enough to prevent crowding out of growth generating activities.

*** insert Figure 1 ***

The intersection of DD and SS determines s_a and g in the social optimum. It can be shown (see Appendix C) that the model is saddlepoint stable if the SS curve cuts the DD curve from above. Intuitively, this can be explained by invoking the correspondence principle. The SS curve gives for each s_a the feasible or *actual* growth rate, conditional on the optimal s_a/s_c ratio (equation 11). The DD curve gives the *desired* growth rate based on intertemporal preferences. To the left of the point of intersection in the stable case, the actual growth rate exceeds the desired one. This is an incentive to lower the actual growth rate by raising abatement spending (along with consumption spending to maintain the optimal abatement consumption ratio).⁹ The difference between the actual and desired growth rate diminishes and an equilibrium is reached if the desired growth rate rises or falls less than the actual growth rate in response to the increase in s_a .

Since only one predetermined variable (K) plays a role in the model, the economy immediately jumps to the balanced growth path due to the saddlepoint stability: the allocation of production over abatement, consumption, and investment is constant, capital grows at rate g and pollution declines at rate $(\gamma - \lambda)g$. However, if such an economy starts with a low capital stock, it may fail to satisfy the ecological viability constraint: eco-systems (and hence the economy) only remain viable if pollution does not exceed the critical level $\bar{P}$. If the capital stock is low, the level of abatement for a given fraction of income spent on abatement (s_a) is low and the level of pollution is high, possibly higher than the maximum admissible upper limit.

The importance of the ecological viability constraint is illustrated by the phase diagram in figure 2. The curve labeled $\bar{P}\bar{P}$ represents the minimum abatement capital ratio for which this constraint ($P \leq \bar{P}$) is satisfied. For constant elasticities γ and λ , the curve is defined by $P = A^\gamma K^\lambda = \bar{P}$ or:

⁹ This is a movement along the downward sloping SS curve.

$$\frac{A}{K} = \bar{P}^{-1/\gamma} K^{-(\gamma-\lambda)/\gamma}, \quad \bar{P}\bar{P} \text{ curve}$$

The line $\dot{a}=0$ represents the saddle path to which the economy jumps if the constraint is not binding. If the initial capital stock is low (say K_0), choosing this path would result in too high a pollution level. For this "poor" economy, it is necessary to choose temporarily higher abatement spending. The optimal trajectory is path BE and from E following the saddle path.¹⁰ For some period, the fraction of production allocated to abatement is determined by the ecological viability constraint ($P=\bar{P}$). The remaining part of production is spent on consumption and investment so that capital and production grow. To prevent pollution from rising over time, abatement spending (A) has to rise, but as long as abatement is relatively effective, i.e. $\gamma > \lambda$, the abatement capital ratio is allowed to decline. When enough capital has been accumulated ($K=\bar{K}$), it becomes optimal to realize a decline in pollution: the economy has outgrown of the ecological constraint and proceeds along the saddle path. If $\gamma=\lambda$, the $\bar{P}\bar{P}$ line is a vertical line. Capital accumulation does not relieve the ecological viability constraint since a constant abatement capital ratio is needed to keep pollution constant. Hence, outgrowing the constraint is not possible then.

*** insert Figure 2 ***

The phase diagram also illustrates the possibility of a low development trap. A very poor economy cannot attain sustainable development. E.g. if the initial capital stock is K_0' , all production is needed for abatement so that capital cannot be accumulated. If investment is reversible, the existing capital stock is gradually transformed into consumption and abatement and falls to zero within finite time. If investment is irreversible, the slightest decline in the capital stock causes the economy to collapse because then pollution cannot be maintained on the ecologically viable level.

5. increased environmental care and optimal growth

Now we turn to the question how a shift in preferences towards more environmental concern affects the optimal rate of growth. Hence, we examine the effects of a rise in ϕ . To highlight the main mechanisms of the model, we restrict this experiment to the case where λ and γ are fixed

¹⁰ Each other path will result in *either* zero consumption and an infinite capital stock, *or* growing consumption until the capital stock is zero and consequently consumption drops to zero. The former cannot be optimal of course (it violates the transversality condition), while the latter violates first order condition (10) on the moment that C drops to zero (cf. Blanchard and Fischer 1989, p.46 and 75).

(i.e. the pollution function is specified as $P=A\gamma K^\lambda$) and to the case that the environmental viability constraint is not binding. We characterize the growth effects by analyzing the shifts in the DD and SS curve. Since the shift in the DD curve depends on the values of γ , λ and ρ_c , it is useful to distinguish the following cases.

$\rho_c = 1$

If $\rho_c = 1$, so that the elasticity of intertemporal substitution is unity and the marginal utility of consumption is not affected by the level of consumption ($\rho = 1$, $U_{cp} = 0$), a shift in environmental preferences (ϕ) changes the optimal growth rate by affecting the SS curve only. By the preference shift, the marginal benefits of abatement rise so that the optimal abatement consumption ratio increases (see equation 11). Equivalently, the consumption abatement ratio falls so that for a given fraction of abatement spending s_a more resources are allocated to investment. This means that the curve SS shifts up. If the DD curve slopes upward, the preference shift induces higher abatement spending which raises the marginal return to saving and therefore the optimal rate of growth. If DD slopes downward, increases in s_a lower the marginal return to savings so that growth is less desired and the optimal growth rate falls.

The interesting question is now when the upward sloping part of the DD curve is relevant. A positive slope requires that the top of DD is situated to the right of the initial level of s_a which is at least $\gamma\chi$. Since, as noted before, the top is at $s_a = \gamma\chi \cdot \beta \cdot \gamma / \lambda$, two conditions must be fulfilled. First, χ must exceed zero. Second, the larger is the initial value of s_a , the more must $\beta \cdot \gamma / \lambda$ exceed 1, which implies by the CRS -condition (5) that the larger must be the gap $\gamma - \lambda$. If abatement is relatively effective (γ large) and capital relatively clean (λ small), increasing abatement spending s_a may increase the marginal product of capital. Hence, it is not only attractive to increase abatement relative to consumption spending, but also to reduce current consumption and raise savings to realize higher growth. The latter is the intertemporal substitution effect, invoked by the rise in the marginal product of capital. Intuitively, the two conditions state that it is only attractive to postpone consumption and realize higher growth in response to increased environmental preferences if there are productivity effects associated with the environment and if abatement technology is successful enough while capital is relatively clean.

The preference parameters ϑ and (the initial value of) ϕ determine the initial value of s_a . The lower is ϑ (this shifts DD up) and the lower is the initial value of ϕ , the lower is the initial value of s_a and the more likely is the upward sloping part of DD relevant. In contrast, a society with high pure rate of time preference ϑ or a low rate of intertemporal substitution $1/\rho$ prefers high levels of current consumption (s_c) and low levels of current pollution (so high levels of abatement s_a) to high rates of growth. As we saw before, if abatement is already high relative to the productivity maximizing level $\gamma\chi$, increasing abatement increases significantly pollution costs, while additional productivity effects are small so that on balance the rate of return and the

incentive to grow fall.

$$\gamma = \lambda$$

If an $x\%$ rise in capital requires an $x\%$ rise in abatement to keep pollution constant, i.e. $\lambda = \gamma$, the steady state rate of intertemporal substitution is independent of ϕ and a rise in ϕ causes only the SS curve to shift upward, while leaving the DD curve unchanged. Furthermore, the DD -curve is downward sloping. The marginal return to capital falls if abatement spending (s_a) increases. Hence, there is by the intertemporal substitution effect an incentive to opt for lower growth in consumption rather than higher growth. With both curves downward sloping, the preference shift unambiguously decreases the optimal growth rate, independent of the size of the intertemporal rate of substitution.

$$\rho_c \neq 1 \text{ and } \gamma > \lambda$$

In the more general case where $\rho_c \neq 1$ and $\gamma > \lambda$, a change in ϕ affects the optimal growth rate by shifting both the SS and the DD curve.

In the case where $\rho_c > 1$, the steady state intertemporal rate of substitution ($1/\rho$) decreases when the concern for the environment increases. This can be explained as follows. As can be checked [see (A9) in the Appendix], the marginal utility of consumption increases with pollution ($U_{c\phi} > 0$). Consumption becomes more (less) valuable if pollution is higher (lower) because consumption can compensate for the disutility of pollution. In other words, consumption and environmental amenities are substitutes. With increased concern for the environment (higher ϕ), changes in pollution have a larger impact on utility. It implies that U_c falls faster for a given rate of decrease in pollution. Along an ecologically sustainable balanced growth path, where pollution is declining, consumers are less willing to postpone consumption, the more pollution affects utility (i.e. the higher is ϕ).

In the case where $\rho_c < 1$, the steady state intertemporal rate of substitution is positively affected by changes in ϕ , since the marginal utility of consumption now decreases with pollution ($U_{c\phi} < 0$). Additional consumption is more enjoyed if pollution is lower. In other words, consumption and environmental amenities are substitutes. Consequently, it provides an incentive to grow faster, since it is attractive to postpone consumption to future periods where pollution is lower and consumption is more enjoyed.

Figure 3 illustrates the effects of a rise in ϕ . SS shifts up. If $\rho_c > 1$, the DD curve shifts downward so that growth may fall even if the upward sloping part of the DD curve was relevant. If $\rho_c < 1$, the DD curve shifts up and optimal growth rate may rise, even if DD is downward sloping in the point of intersection. It is interesting to note that s_a may fall in response to the preference shift towards more environmental concern. In this paradoxical situation, a higher level of pollution is accepted since it is compensated by a higher rate of pollution reduction over time and

a higher growth rate of consumption. Figure 4 gives some numerical results for the relation between ϕ , ρ_c and the optimal growth rate. It can be concluded that the less willing to postpone consumption the society is (i.e. the higher ρ_c is), the more likely a rise in environmental preferences (ϕ) will decrease the optimal rate of growth.

*** insert Figures 3 and 4 ***

Summing up, if ecologically sustainable balanced growth paths are feasible, environmental preferences affect the optimal rate of growth. When pollution is constant in the steady state ($\gamma=\lambda$), an increased preference for the environment will depress the optimal rate of growth. In the case that abatement is relatively effective so that pollution falls along a balanced growth path ($\gamma>\lambda$), the optimal growth rate may increase in response to a small shift towards more concern for the environment only if improvements in the quality of the environment boost the productivity of physical capital ($\chi>0$), if the initial preference parameter for a clean environment (ϕ) is rather low, and if the social discount rate (ϑ) is small or if the intertemporal rate of substitution ($1/\rho_c$) is high.

6. Market equilibrium and environmental policy

An increase in environmental care in a market economy should be distinguished from that in a first-best economy. Pollution is an externality in many respects for private agents. Increased interest in environmental issues leads to environmental policy that creates incentives to internalize these externalities. Here, this kind of policy is studied for a perfectly competitive economy consisting of many infinitely living representative consumers and n (where n is large) individual, symmetric firms.

The consumer problem is to maximize utility function (13) above by choosing consumption subject to the usual intertemporal budget constraint. This yields $c/c = [r + \phi(\rho_c - 1)\dot{P}/P - \vartheta]/\rho_c$, where r is the market rate of interest. In a situation of balanced growth this boils down to:

$$r = \vartheta + \rho g. \quad (16)$$

Each representative firm i maximizes profits by determining the level of capital (K_i) it employs and the level of abatement spending. As before, firms suffer from pollution: e.g. smoke in the air and noise reduce the health and productivity of its workers. However, only part of this pollution is caused by the firm's own actions, while pollution of other firms, partly transmitted through the air, also affects the firm's working conditions. Hence production depends besides on private

capital inputs (K_i), also on the firm's own pollution (per m^3 air), P_i , and the pollution (per m^3 air) caused by other firms. Firms only internalize the effects of own pollution on production (measured by elasticity $\tilde{\chi}$), which is smaller than the social effect of pollution on aggregate production (as before measured by χ , so $\tilde{\chi} < \chi$).

In the symmetric equilibrium, each firm has the same pollution per m^3 air, which equals the economy-wide level of pollution per m^3 air (P), and the same capital input, abatement and production level, which are aggregated to $K=nK_i$, $A=nA_i$ and $Y=nY_i$. The production elasticity of capital and the pollution elasticities of capital and abatement are given by β , λ , and γ respectively, restricted by equation (5), so that on the aggregate level the production structure is as in the previous sections and aggregate balanced growth is feasible.

The maximization problem of the firm reads:

$$\max. \int_0^{\infty} [(1-\tau_y)Y_i - (1-\tau_a)A_i - \tau_p P_i - I_i] e^{-\int_0^t r(s)ds} dt, \quad (17)$$

$$\begin{aligned} \text{s.t.} \quad Y_i &= \tilde{Y}(K_i, P_i, P), & \beta &= \tilde{Y}_{K_i} K_i / Y_i, & \tilde{\chi} &= \tilde{Y}_{P_i} P_i / Y_i < \chi, & \tilde{Y}_P P / Y_i &= \chi - \tilde{\chi}, \\ P_i &= P(A_i, K_i), \\ \dot{K}_i &= I_i \end{aligned}$$

Abatement is subsidized at rate τ_a , pollution is taxed at rate τ_p , while τ_y is a value added tax. The first order conditions are:

$$[(1-\tau_y)(\beta - \lambda\tilde{\chi}) - \lambda\tau_p(P_i/Y_i)]y = r, \quad (18)$$

$$s_a = \frac{(1-\tau_y)\gamma\tilde{\chi} + \gamma\tau_p(P_i/Y_i)}{1-\tau_a}. \quad (AA\text{-line}) \quad (19)$$

The first condition equates the private marginal return to capital, taken into account the tax obligations and the firm's own pollution effects associated to capital, to the market rate of interest. The second condition equates the private marginal cost of abatement, consisting of after-subsidy expenditures on abatement goods, to the private marginal benefit of abatement, which consist of the (after-tax) productivity gain through the reduction in the firm's own pollution and the reduction in the pollution tax obligation.

Balanced growth (with constant r and s_a) requires constant tax rates τ_y and τ_a , while τ_p must increase at rate $(1+\gamma-\lambda)g$ so that $\tau_p P_i/Y_i \equiv \bar{\tau}_p$ is constant. Since production grows, firms can finance the pollution tax obligation due to a given pollution level out of growing revenues. Consequently, a constant pollution tax τ_p would imply a tax burden declining over time, and the incentive for abatement would diminish over time. Hence, the pollution tax τ_p must rise over time to prevent growing pollution.

The market equilibrium is given by (6), (16), (18) and (19), solving for g , s_a , s_c and r . Figure 5 depicts the solution for g and s_a as the intersection of line AA and the curve MM . The latter is derived by eliminating r from (16) and (18):

$$g = \frac{[(1 - \tau_y)(\beta - \lambda \bar{\chi}) - \bar{\tau}_p \lambda] y(s_a) - \vartheta}{\rho} \quad (MM \text{ curve}) \quad (20)$$

The line AA represents the profit maximizing s_a , which is independent of g . The curve MM represents for each s_a the desired rate of growth in the market economy. The desired rate of growth increases in s_a . An increase in abatement raises the productivity of capital in terms of physical output so that the marginal rate of return increases. This implies that the market rate of return rises and that consumers increase consequently savings.

*** insert Figure 5 ***

In the absence of intervention, abatement is too low in the market economy [compare (11) to (19)] for two reasons: the effects of private abatement on other firms' productivity and the effect of pollution on consumers' utility are ignored by producers. Hence introducing a subsidy on abatement ($\tau_a > 0$) or a tax on pollution ($\bar{\tau}_p > 0$) will improve welfare. Moreover, by comparing MM [equation (20)] to DD [equation (14)], it can be seen that, in absence of the value added tax, for each $s_a > \gamma\chi$ the desired rate of growth in the market economy is larger than in the social optimum (MM is situated above DD). The reason is that the market rate of return to savings (r) is too high since it fails to reflect the negative effects of an additional unit of capital on other firms' productivity and on utility. Only own pollution effects on own productivity ($\bar{\chi}$) are reflected. Formally, from (18), (11), and (14) follows for given s_a : $r - r' = [\gamma(\chi - \bar{\chi}) + \lambda\phi s_c] y$, where r' is the social rate of interest defined above. A tax on economic activity or pollution ($\tau_y > 0$ or $\bar{\tau}_p > 0$) can redress this externality.

Now consider the question how environmental policy, i.e. the introduction of the optimal tax and subsidy, will affect the rate of growth. There are two counteracting effects. On the one hand, the policy has to remove the externality arising from the fact that firms only take into account direct productivity effects while aggregate productivity effects are larger (i.e. $\bar{\chi} < \chi$). The productivity gains from abatement are larger than perceived by individual firms. Internalization of this *productivity externality* stimulates growth¹¹: abatement activities are then exploited to

¹¹To prove this, we need to compare the market rate of growth (where $s_a = \gamma\bar{\chi}$) and the optimal growth rate for $\phi = 0$ (where $s_a = \gamma\chi$). With constant elasticity of $y(s_a)$, it can be derived from (5),

(11), (14), (20) and (21) that: $\frac{\rho g^m + \vartheta}{\rho g^* + \vartheta} = \left(\frac{\beta - \lambda \bar{\chi}}{\beta - \lambda \chi} \right) \left(\frac{\bar{\chi}}{\chi} \right)^{\frac{\gamma\chi}{1 - \gamma\chi}} < 1$ since $\bar{\chi} < \chi \wedge \gamma\chi < 1$.

maximize after-abatement-allowances returns to capital. On the other hand, the subsidy has to raise abatement further because pollution is a disutility ($\phi > 0$), which is not taken into account by firms in deciding on abatement spending. The internalizing of this *environmental amenity externality* is very similar to a rise in ϕ in the social optimum (from $\phi=0$ to $\phi>0$). As illustrated in Figure 5, the internalizing of this externality will depress the growth rate unless ϕ and ϑ are small and $\gamma > \lambda$ (since then the (social) marginal return to capital raises, i.e. the upward sloping part of DD is relevant). On balance, the implementation of the optimal environmental policy to internalize both externalities may raise growth if the external effects of pollution on productivity are large ($\chi - \bar{\chi}$ large) relative to the disutility of pollution (ϕ small).

How should the tax instruments be implemented to attain the first-best outcome in the decentralized economy? Introducing the pollution tax only is sufficient. The expression for the optimal pollution tax is found by equating the private and social abatement ratio [in (19) and (11)], and equating the private and social rate of return [in (18) and (14)], with $\tau_a = \tau_y = 0$:

$$\bar{\tau}_p^{**} = (\chi - \bar{\chi}) + \phi s_c^{**}, \quad (21)$$

where a double asterisk (**) denotes the optimal level of a variable. The optimal tax is determined by two components which reflect the productivity externality ($\chi - \bar{\chi}$) and the amenity externality (ϕs_c^{**}). Since the government budget, expressed as a fraction of national production, equals $\tau_p P_i / Y_i \equiv \bar{\tau}_p$, equation (21) reveals that this policy yields a budget surplus: pollution is a source of revenue. However, in practice a tax on pollution may be difficult to implement due to measurement problems and due to the fact that the optimal tax rate should grow steadily. Therefore, it is worthwhile to consider a policy relying on the other two instruments.

The value added tax alone is not sufficient. The reason is that achieving the optimal optimal abatement level requires subsidizing production which is to be considered as the indirect return of abatement ($\tau_y < 0$), while, as noted before, achieving the optimal private return to capital requires taxation ($\tau_y > 0$). Neither is the abatement subsidy alone sufficient, since this instrument can not influence directly the marginal return to capital. Hence, both instruments are necessary. The optimal rates and the corresponding excess of tax revenues over the abatement subsidy expenditures (expressed as a fraction of aggregate output) are given by:

$$\tau_y^{**} = \lambda [(\chi - \bar{\chi}) + \phi s_c^{**}] \left(\frac{1}{\beta - \lambda \bar{\chi}} \right), \quad (22)$$

$$\tau_a^{**} = \gamma [(\chi - \bar{\chi}) + \phi s_c^{**}] \left(\frac{1}{\beta - \lambda \bar{\chi}} \right) \frac{\beta}{s_a^{**}}, \quad (23)$$

$$\tau_y^{**} - \tau_a^{**} s_a^{**} = -(\gamma - \lambda) [(\chi - \bar{\chi}) + \phi s_c^{**}] \left(\frac{1 - \gamma \chi}{\beta - \lambda \bar{\chi}} \right), \quad (24)$$

where condition (5) is used to derive (24).

First note that $\tau_a = 1$ if $\tilde{x} = 0$: in the absence of intervention firms do not internalize any effect of pollution, abatement spending would be zero and should be financed entirely by the government. Second, the government budget shows a deficit, unless $\lambda = \gamma$, i.e. unless the polluting effects of $x\%$ growth in capital can be offset by $x\%$ growth in abatement spending. The environmental amenity externality ($\phi > 0$) requires a reduction in pollution (relative to the situation where $\phi = 0$) through two channels: reducing the capital intensity of production and stimulating abatement. If $\lambda = \gamma$, both channels are equally productive and it is efficient to stimulate abatement exactly to the same amount as to which the use of capital is reduced. In contrast, in the case where abatement is relatively effective and capital is only weakly polluting ($\gamma > \lambda$), it is efficient to tax capital only moderately (by τ_y) and to subsidize abatement heavily so that a budget deficit arises. In that case, a lumpsum tax is necessary to sustain the first best outcome.

6. Conclusion

The model presented in this paper highlights some essential aspects of the interaction between economic growth and pollution. First, we derived the conditions for feasibility and optimality of economic growth in a one sector endogenous growth model where pollution is a side-product of the utilization of capital and where pollution can be reduced by spending part of the aggregate output on abatement. Second, we traced the growth effects of environmental policy, which was interpreted either as a shift in preferences towards more concern for a clean environment or as the introduction of taxes to internalize the externalities associated with the environment. The results may be reframed in terms of the debate on the desirability and the pace of growth in view of environmental problems.

Those who are pessimistic argue that if pollution is an inevitable side-product of economic activity and if the absorption capacity of the ecological system is limited, growth in economic activity cannot be ecologically sustainable. However, as is shown here, a growing economy can produce a growing amount of abatement devices, so that, provided that abatement activities are effective enough relative to the polluting content of production activities, pollution stays constant or may even fall if the economy grows (in terms of the model: $\gamma \geq \lambda$).

A second reason to be pessimistic is that there may be diminishing returns with respect to reproducible production factors due to ecological limits, so that growth cannot be sustained. There is, however, neither *a priori* reason nor empirical evidence to believe so. There may be constant returns with respect to the reproducible production factors (K and A), so that long-term balanced growth is feasible. In that case, the growth rate is endogenous: investment decisions and environmental policies affect the long term-rate of growth. Nonzero growth may be optimal.

But even if long-term growth is sustainable and optimal, there might be an inverse relationship between environmental care and long-term optimal growth, because increased abatement activities may crowd out growth generating activities. We showed that this negative effect on growth should be confronted with two positive effects. First, there may be productivity effects: a higher quality of the environment improves the productivity of production factors. Second, the marginal productivity of investment goods may rise. Then, it is optimal to reduce current levels of consumption to give way to both higher abatement and higher investment levels, as a process of intertemporal substitution. Hence, the optimal growth rate may rise when preferences shift towards more environmental concern, if there are productivity effects, if the marginal cost of abatement activities is low, and if consumers are patient enough to postpone consumption.

A final reason to be pessimistic is the existence of externalities associated to pollution problems. The market equilibrium may be characterized by a growth rate that is too high, because the amenity value of the environment is ignored by producers. A pollution tax or subsidy of abatement activities and taxes on polluting economic activities have to be introduced to redress the externalities. However, also here pessimism may be premature. It is possible that growth in the market equilibrium is too low, because aggregate productivity effects of a clean environment are ignored by individual producers. Introducing the right taxes then leads to higher growth. Because of the productivity externality, environmental policy that improves the quality of the environment affects positively the productivity of production factors so that growth may rise. The government budget need not impose strong restrictions on the environmental tax policy because taxation of pollution yields revenues and an abatement subsidy can at least partly be financed by a value added tax revenue.

Of course, we need an empirical assessment of scale economies, abatement possibilities, productivity effects, *etc.* to know whether pessimism or optimism is justified. Moreover, there are various ways to extend the present model that may be useful in the debate on growth and the environment. First, labour can be introduced explicitly as a production factor (cf. Gradus and Smulders 1993). Second, technological progress in pollution saving technology may be important (cf. Bovenberg and Smulders 1993). Finally, public finance issues may be elaborated, such as different forms of taxation, second-best situations, and publicly provided abatement (cf. Ligthart and Van der Ploeg 1993).

Appendix A

Specifications of the instantaneous utility function that guarantee balanced growth

Here we derive which specification(s) of the instantaneous utility function $U(c, P)$ satisfy the conditions for balanced optimal growth. As explained in the main text, preferences should feature the following characteristics:

- (i). Ex hypothesi, consumption c is a utility and pollution P is a disutility:

$$U_c > 0 \text{ and } U_P < 0. \quad (\text{a priori requirements}) \quad (\text{A1})$$

- (ii). The maximization problem should be concave in the instruments c and A :

$$U_{cc} < 0 \text{ and } U_{PP}P_A P_A + U_{PP}P_{AA} < 0 \quad (\text{concavity requirements}) \quad (\text{A2})$$

- (iii). Along a balanced growth path where c and P grow at possibly different rates, the direct elasticity of marginal utility of consumption (ρ_c), the relative weight of the environment in utility (ϕ) and the elasticity of marginal utility of consumption with respect to pollution should be constant:

$$\begin{aligned} -U_{cc}c/U_c (\equiv \rho_c) \text{ and } -U_P P/U_c c (\equiv \phi) \text{ and } U_{cP}P/U_c \text{ are independent of the level of } c \\ \text{and } P. \end{aligned} \quad (\text{Balanced growth requirements}) \quad (\text{A3})$$

First, we find the specification for $U(c, P)$ with constant elasticity of marginal utility of consumption: $-U_{cc}c/U_c \equiv \rho_c$ is constant or

$$\frac{d \ln U_c}{dc} = \frac{-\rho_c}{c} \quad (\text{A4})$$

Integration yields:

$$\ln U_c = -\rho_c \ln c + \ln N(P) \quad \Rightarrow \quad U_c = c^{-\rho_c} N(P) \quad (\text{A5})$$

where the constant of integration is defined as $\ln N(\cdot)$, which of course may depend on any other variable than c , and hence may depend on the second argument of the utility function, P . Integration of (A6) yields:

$$U(c, P) = \begin{cases} \frac{c^{1-\rho_c}}{1-\rho_c} N(P) + M(P) & \text{for } \rho_c \neq 1 \\ \ln c \cdot N(P) + M(P) & \text{for } \rho_c = 1 \end{cases} \quad (\text{A6})$$

where $M(P)$ is the constant of integration. Now calculate from these specifications:

$$-U_P P/U_c c \equiv \phi = \begin{cases} \frac{-1}{1-\rho_c} \frac{N'P}{N} - \frac{M'P}{Nc^{1-\rho_c}} & \text{for } \rho_c \neq 1 \\ -\frac{N'P}{N} \ln c - \frac{M'P}{N} & \text{for } \rho_c = 1 \end{cases} \quad (\text{A7})$$

If $\rho_c \neq 1$, ϕ is independent of the levels of c and P only if $M' = 0$ and $N'P/N$ is constant. Then

$\phi = -(N'P/N)/(1-\rho_c)$, or equivalently, the elasticity of $N(P)$ is equal to the constant $N'P/N = -\phi(1-\rho_c)$. Therefore $N(P)$ takes the form $N(P) = \bar{N} \cdot P^{-\phi(1-\rho_c)}$ and $M(P) = \bar{M}$, where $\bar{N}$ and $\bar{M}$ are constants.

If $\rho_c = 1$, ϕ is independent of the levels of c and P only if $N' = 0$ and $M'P$ is constant. Then $\phi = -M'P/\bar{N}$, where $\bar{N}$ is a constant, or equivalently, $M'(P) = -\phi\bar{N}/P$. Integrating this last expression shows that $M(P)$ takes the form $M(P) = -\phi\bar{N} \ln P + \bar{M}$.

Substituting these results into (A6) yields:

$$U(c, P) = \begin{cases} \bar{N} \frac{(cP^{-\phi})^{1-\rho_c}}{1-\rho_c} + \bar{M} & \text{for } \rho_c \neq 1 \\ \bar{N}(\ln c - \phi \ln P) + \bar{M} & \text{for } \rho_c = 1 \end{cases} \quad (\text{A8})$$

As can be checked

$$U_{cP}P/U_c = \phi(\rho_c - 1) \quad \text{for each } \rho_c. \quad (\text{A9})$$

Hence, the specification in (A8) satisfies condition (iii). To satisfy condition (i), we must have $\phi > 0$ and $\bar{N} > 0$. Without loss of generality, $\bar{N}$ can be set to unity since it is a shift factor in the ordinal utility function, while the additive term $\bar{M}$ can be set to zero. This yields equation (13).

Finally, condition (ii) has to be satisfied. For $U_{cc} < 0$ we must require $\rho_c > 0$. Concavity in A imposes restrictions on the pollution function:

$$-\frac{P_{AA}A/P_A}{P_AA/P} < \frac{U_{PP}P}{U_P} = -\phi(1-\rho_c) - 1. \quad (\text{A10})$$

Note that if the pollution function is specified as $P(A, K) = A^{-\gamma}K^\lambda$, then the LHS of (A10) equals $-(1+\gamma)/\gamma$ so that $1/\gamma$ must exceed $\phi(1-\rho_c)$. Hence, $\rho_c > 1$, which is the empirical relevant value, is sufficient for concavity.

Appendix B: Pollution as a stock

With respect to several environmental problems, the effects of *accumulated* pollution on ecological systems, production, and welfare are more pronounced than *flow* effects of pollution. E.g. the acidification of the soil, which damages both ecological systems and environmental amenities like landscapes, or the break-down of the ozone layer are processes that will not stop once their direct causes, i.e. pollution like carbon-emissions, are curbed, but only after the stock of accumulated pollution is assimilated or broken down. Modelling pollution as a stock (cf. Tahvonen and Kuuluvainen 1990, Bovenberg and Smulders 1993) is therefore more realistic, but it complicates our framework without affecting qualitatively our (steady state) conclusions. This is shown here by amending the model and reducing it to a diagram in the g, s_a plane which is basically the same as in the main text.

The accumulation of pollution is represented by:

$$\dot{S} = P(A, K) - N(S) \quad (B1)$$

The flow of pollution P adds to the stock of pollution S , and a certain part $N(S)$ of this stock is broken down each period due to the assimilative capacity of the environment. In the simplest specification, a fixed proportion (δ) of the stock can be assimilated so that $N(S) = \delta S$. If, on the other hand, further accumulation of wastes deteriorates the absorption capacity of nature, we must assume: $N'S/N < 1$.

The stock of pollution S rather than the flow P now matters, so we replace P by S in the production function (1), the utility function [(8) and (13)], and the definitions of χ and ϕ . The condition for ecological sustainability is amended into $S < \bar{S}$. This precludes that S grows at a constant positive rate, which requires in view of (B1) that the flow of pollution in the steady state does not exceed the absorption capacity of nature: $P \leq N(S)$. Consequently, the flow of pollution is not allowed to rise over time so that restriction (7) is again a condition for ecologically sustainable balanced growth.

For balanced growth to be feasible, further restrictions are to be imposed. Consider first the simplest specification of the waste accumulation function (B1). If $N(S) = \delta S$, the stock of pollution can grow or fall at a constant proportionate rate by maintaining a constant P/S ratio. Since the flow of pollution declines at rate $(\gamma - \lambda)g$, the stock of pollution will decline at the same rate. Endogenous growth requires constant returns with respect to the reproducible factors, so again restriction (5) is necessary. However, if nature's assimilative capacity is featured by $N'S/N < 1$, a constant rate of decline of the flow P results in a non-constant (viz. increasing) rate of decline in S so that balanced growth is only feasible if P is constant in the steady state, i.e. if $\lambda = \gamma$. Below, we work out the case $N(S) = \delta S$, which also incorporates the special case of constant steady state level of pollution by taking $\lambda = \gamma$.

The fact that S and P will change at the same rate in the long-run makes already intuitively clear that the growth effects in the model with pollution as a stock (the "stock-model") must

resemble those in the model with pollution as a flow (the "flow-model"). Also the level effects are similar in both models, since the long-run level of S is directly and positively related to that of P . The main difference is that pollution as a stock introduces additional intertemporal aspects.

The planning economy maximizes welfare [(8) and (13)], subject to (2) and (B1). First order conditions are:

$$U_c = \theta_1, \quad (B2)$$

$$\theta_3 P_A = \theta_1, \quad (B3)$$

$$\theta_1 Y_K + \theta_3 P_K = \vartheta \theta_1 - \dot{\theta}_1, \quad (B4)$$

$$U_S + \theta_1 Y_S - \theta_3 N_S = \vartheta \theta_3 - \dot{\theta}_3, \quad (B5)$$

where θ_3 denotes the costate variable for pollution accumulation. Combining (B2), (B3) and (B4) yields, after applying the definitions of the elasticities, the DD curve which is for the long-run exactly the same as in the main text [eq. (14)]. We assume again that the production function and the pollution function are of the Cobb-Douglas type (so β , χ , λ , and γ are constants) and that $N_S = \delta$. In the steady state, $\dot{S}/S$ is constant, so P/S is constant, and $\dot{S}/S = \dot{P}/P = -(\gamma - \lambda)g$. The steady state P/S ratio follows from (B1):

$$P/S = \delta - (\gamma - \lambda)g.$$

Combining this result with the production function, taking into account (5), gives the steady state output capital ratio:

$$\frac{Y}{K} = \alpha_y K^{\beta-1} S^{-\chi} = \left(\alpha_y s_a^{\gamma\chi} [\delta - (\gamma - \lambda)g]^{-\chi} \right)^{1/(1-\gamma\chi)} \equiv y(s_a, g). \quad (B6)$$

Differentiating (B3) and eliminating $\dot{\theta}_1/\theta_1$ using (B2) and (13) yields:

$$\dot{\theta}_3/\theta_3 = (1 + \gamma - \lambda - \rho)g.$$

Substituting this result into (B5) and rewriting gives:

$$s_a = \left(\frac{1}{\psi} \right) \gamma (\phi s_c + \chi), \quad \text{where } \psi = 1 + \frac{\vartheta + (\rho - 1)g}{\delta - (\gamma - \lambda)g}. \quad (B7)$$

This equation relates optimum abatement spending and consumption spending. It is identical to equation (11) of the flow-model, apart from the factor $1/\psi$. Note that if $\delta \rightarrow \infty$, i.e. if the stock effects of pollution are negligible because assimilation is very fast, $\psi \rightarrow 1$ so that (11) and (B7) are identical. Furthermore, note that $\vartheta + (\rho - 1)g = r^* - g > 0$ and that $\delta - (\gamma - \lambda)g > 0$ [see (B6)], so that

$\psi > 1$: abatement spending relative to consumption spending is less than in the flow-model because the benefits from abatement arise only after the stock of pollution is adjusted which takes time. The higher time preference and the lower the assimilation capacity of nature (which equals the adjustment speed of S), the lower will be abatement spending *ceteris paribus* relative to the flow-model ($\partial\psi/\partial\theta > 0$, $\partial\psi/\partial\delta < 0$).

Eliminating s_c between the goods market equilibrium equation (6) and (B7) yields the *SS*-curve, which is implicitly defined by:

$$0 = g - \left[\left(1 + \frac{\chi}{\phi} \right) - \left(1 + \frac{\psi(g)}{\phi\gamma} \right) s_a \right] y(s_a, g) \equiv F(s_a, g). \quad (\text{SS-curve}) \quad (\text{B8})$$

To examine the properties of the *SS*-curve, calculate:

$$\begin{aligned} \frac{\partial F}{\partial s_a} &= \frac{y}{s_a} \left(\frac{1}{\phi\gamma} \right) \left(\frac{1}{1-\gamma\chi} \right) \left[s_a - \left(\frac{\gamma\chi}{\psi} \right) \left(\frac{\phi\gamma + \gamma\chi}{\phi\gamma + \psi} \psi \right) \right], \\ \frac{\partial F}{\partial g} &= 1 + \left(\frac{\chi}{1-\gamma\chi} \right) \frac{(\gamma-\lambda)g}{\delta - (\gamma-\lambda)g} + \frac{s_a y}{\phi\gamma} \frac{\partial \psi}{\partial g}, \\ \frac{\partial F}{\partial \phi} &= - \frac{\psi}{\phi\gamma} \left[s_a - \frac{\gamma\chi}{\psi} \right]. \end{aligned}$$

In normal cases, the first two derivatives are positive. Then the slope of the *SS*-curve is negative as in the flow-model, since by the implicit function rule $dg/ds_a|_{ss} = -(\partial F/\partial s_a)/(\partial F/\partial g)$. A sufficient (but far from necessary) condition for $\partial F/\partial s_a > 0$ is $\psi(\phi\gamma + \gamma\chi)/(\phi\gamma + \psi) < 1$ since $s_a > \gamma\chi/\psi$ as appears from (B7). This condition is satisfied for $\phi\gamma + \gamma\chi < 1$. A sufficient (but far from necessary) condition for $\partial F/\partial g > 0$ is $\partial\psi/\partial g > 0$, which is satisfied for $\rho_c > 1 - (\gamma-\lambda)\theta/[1 + (\gamma-\lambda)\phi]$. This is a mild condition in view of the empirical relevant value of $\rho_c \geq 1$.

The *SS* curve shifts upwards for an increase in ϕ since $\partial g/\partial \phi|_{ss} = -(\partial F/\partial \phi)/(\partial F/\partial g) > 0$ for the relevant values of s_a [see (B7): $s_a > \gamma\chi/\psi$].

Summing up, the *DD*-curve remains unchanged, while the *SS*-curve slopes downward and shifts in the same direction as in the flow-model. Hence, the qualitative properties of the model remain the same (for the long-run) whether pollution matters as a flow or as a stock.

Appendix C: stability of the model

Here we proof that the optimal growth model of section 3 is saddle point stable at least for a sufficiently large value of the preference parameter ρ_c , by reducing the model to a differential equation in the single variable $a \equiv A/K$ and showing that this equation has a positive root.

First, we rewrite the model in the variables K , $a \equiv A/K$, and $x \equiv C/K$. Equations (11), (12) and (2) can be rewritten as:

$$x = (1/\phi\gamma) (a - \gamma\chi y), \quad (C1)$$

$$\beta y - (\lambda/\gamma)a = \vartheta + \delta_K + \rho_c(\dot{x}/x) + \phi\gamma(\rho_c - 1)(\dot{a}/a) + \rho(\dot{K}/K), \quad (C2)$$

$$\dot{K}/K = y - a - x - \delta_K, \quad (C3)$$

where we introduced capital depreciation at rate δ_K (in the main text $\delta_K=0$). From the Cobb-Douglas production function and (5), we can derive for the output capital ratio ($y \equiv Y/K$):

$$y = \alpha_Y a^{\gamma\chi}. \quad (C4)$$

Differentiating (C1) gives:

$$\frac{\dot{x}}{x} = f(a) \frac{\dot{a}}{a}, \quad \text{where } f(a) \equiv \frac{a^{1-\gamma\chi} - \alpha_Y(\gamma\chi)^2}{a^{1-\gamma\chi} - \alpha_Y(\gamma\chi)}. \quad (C5)$$

Using (C1), (C3), (C4) and (C5) to eliminate y , x , $\dot{K}/K$, and $\dot{x}/x$ in (C3) respectively, yields the following differential equation in a as the reduced form of the model:

$$\dot{a} = \frac{a}{\rho_c f(a) + \phi\gamma(\rho_c - 1)} \{B_1 a^{\gamma\chi} + B_2 a + B_3\}, \quad (C6)$$

$$\begin{aligned} \text{where } B_1 &\equiv -[1 + (\gamma - \lambda)\phi] (\rho_c(1 + \chi/\phi) - 1) \alpha_Y \\ B_2 &\equiv [1 + (\gamma - \lambda)\phi] (\rho_c(1 + 1/\phi\gamma) - 1) \\ B_3 &\equiv -[\vartheta + (1 - \rho)\delta_K] \end{aligned}$$

The model is saddlepoint stable if the RHS of (C6) is increasing in a , at least for values of a around the steady state solution (say $a=a^{**}$, defined by $\dot{a}=0$). Consider now the relevant range for a . In an interior solution, a is restricted by $x \geq 0$ (consumption is nonnegative) and $a+x \leq y$ (the sum of consumption and abatement does not exhaust production). Taking into account (C1) and (C4), this yields the bounds for a :

$$a \equiv (\alpha_Y \gamma \chi)^{1/(1-\gamma\chi)} \leq a \leq \bar{a} \equiv \left(\alpha_Y \frac{\gamma \chi + \phi \gamma}{1 + \phi \gamma} \right)^{1/(1-\gamma\chi)}. \quad (C7)$$

We use (C7) in determining whether the factor in accolades in (C6) is increasing in a . A necessary condition for the latter is :

$$B_1 \gamma \chi > -B_2 a^{1-\gamma\chi}. \quad (C8)$$

Given the signs of B_1 and B_2 , we can distinguish three cases:

- (i) $\rho_c > \phi\gamma/(\gamma\chi + \phi\gamma)$, so that $B_1 < 0$ and $B_2 > 0$. In this case (C7) is satisfied if:

$$a > \left(\frac{-B_1}{B_2} \gamma\chi \right)^{1/(1-\gamma\chi)} = \left[\alpha_Y \gamma\chi \left(\frac{\gamma\chi + \phi\gamma - \phi\gamma/\rho_c}{1 + \phi\gamma - \phi\gamma/\rho_c} \right)^{1/(1-\gamma\chi)} \right] \quad (C9)$$

Since the RHS is smaller than the lower bound $\bar{a}$, the inequality is satisfied indeed.

- (ii) $\phi\gamma/(1 + \phi\gamma) < \rho_c < \phi\gamma/(\gamma\chi + \phi\gamma)$, so that $B_1 > 0$ and $B_2 > 0$. In this case (C7) is satisfied if $(-B_1/B_2)\gamma\chi < a^{1-\gamma\chi}$. Since the LHS is negative, the inequality is satisfied.
- (iii) $\rho_c < \phi\gamma/(1 + \phi\gamma)$, so that $B_1 > 0$ and $B_2 < 0$. In this case (C7) is satisfied if inequality (C9) with the inequality sign reversed is satisfied, implying that a should be below its lower bound, which is of course never the case in an interior solution.

Hence for $\rho_c > \phi\gamma/(1 + \phi\gamma)$, the factor in accolades in (C6) is increasing in a . The differential equation (C6) then has a positive root if the premultiplying factor is positive. This is indeed the case for $\rho_c > \phi\gamma/(1 + \phi\gamma)$. Note that $f'(a) < 0$. Hence $f(\bar{a})$ yields the minimum relevant value for $f(a)$. Substituting the minimum value both for ρ_c and for $f(a)$ yields for the denominator of the premultiplying factor:

$$\frac{\phi\gamma}{1 + \phi\gamma} \left[\left(\frac{(\gamma\chi + \phi\gamma) - (1 + \phi\gamma)(\gamma\chi)^2}{(\gamma\chi + \phi\gamma) - (1 + \phi\gamma)(\gamma\chi)} \right) - 1 \right],$$

which is positive since $\gamma\chi < 1$, so that the entire factor is positive.

Now we can conclude that, at least for $\rho_c > \phi\gamma/(1 + \phi\gamma)$, $\dot{a}$ is increasing in a so that the model is saddlepoint stable. This implies that $a = A/K$, and all other variables, immediately jump to their steady state values.

It can be shown that the stability condition stated in the main text is equivalent with the argument stated here. The downward sloping SS -curve should be steeper than the DD -curve, or equivalently, the difference between the two slopes should be negative. Calculating this difference and substituting the definitions of B_1 and B_2 , this conditions can be written as:

$$-\frac{\alpha_Y}{a} \left(\frac{1/\rho}{1 - \gamma\chi} \right) [B_2 a^{1-\gamma\chi} + B_1 \gamma\chi] < 0,$$

which is equivalent to (C8) if $\rho > 0$.

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Figures

Figure 1 Optimal growth and increased environmental care for logarithmic utility ($\rho_c = 1$)

The broken lines represent an increase in the preference for the environment ($d\phi > 0$)

Figure 4 $dg/d\phi$ and $ds_a/d\phi$ for alternative values of ρ_c
 ($\lambda=0.2$, $\gamma=1.4$, $\chi=0.02$, $\vartheta=0.10$, $\alpha_1=0.168424$)

Figure 5 Market equilibrium and Internalizing the environmental externalities

Internalizing the productivity externality raises s_a from $\gamma\bar{\chi}$ to $\gamma\chi$, and g from g^m to g^* .

Internalizing the environmental amenity externality in addition raises s_a from $\gamma\chi$ to $s_a^{**} = \gamma\chi + \gamma\phi s_c^{**}$, and changes g from g^* to g^{**} .

a. $\chi - \bar{\chi}$ large, ϕ and ϑ small: $g^{**} > g^m$

b. $\chi - \bar{\chi}$ small, ϕ and ϑ large: $g^{**} < g^m$

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