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Green Attitude and Economic Growth

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Abstract We analyze the interdependence between green attitude and equilibrium development of environmental quality in an endogenous growth model. Individuals take only part of their impact on pollution into account, hence there is a negative externality of capital accumulation on environmental quality. Increasing wealth or increasing pollution enhance green attitude and reduce the externality, because individuals care more about the environment if their income is higher or if pollution is more obvious. The time path of pollution as well as the evolution of equilibrium growth are shown to depend crucially on the determinants of green attitude. Ongoing growth may lead to complete internalization of the environmental externality if green attitude improves with increasing wealth, e.g. as a consequence of an increase in environmental education. In contrast, if green attitude is determined exclusively by the level of environmental quality, pollution remains at a suboptimally high level. The interdependence of wealth and pollution in the determination of environmental awareness implies more complex dynamics. Capital growth enhances green attitude and thereby decreases pollution. Improved environmental quality in turn may increase capital growth due to less green attitude and therefore slow down convergence to the sustainable balanced growth path.

Keywords Pollution · Endogenous growth · Green attitude

JEL Classification O1 · O4 · Q2 · Q5

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1 Introduction

Recent research in various disciplines identifies an increased sensitivity of individuals as regards environmental problems such as pollution, loss of biodiversity, global warming, ozone depletion or tropical deforestation. Summarizing this, the European Commission (2008, p. 3) states within the Special Eurobarometer 295 entitled 'Attitudes of European Citizens towards the Environment' that: "…citizens are becoming more aware of both the potential effects of these problems in their daily lives and the role they could play in protecting their environment." Follow-up studies confirm these preoccupations (see e.g. European Commission 2014).

Bretschger and Smulders (2007, p. 1) already emphasize the importance of social dynamics in the context of environmental quality evolution because of learning behavior or changing perception. In industrialized economies, perception of environmental issues strengthens over time, e. g. by increasing pollution, environmental education or increasing income. Hence, individual awareness of environmental degradation is endogenous and as a consequence, pollution and accumulation dynamics become considerably more complex. We focus on the determinants of environmental externalities as well as on their evolution on the growth path. We show that the properties of dynamic market equilibrium depend crucially on whether and in which way individual attitude towards the environment is influenced by economic development. The relevance of pollution perception for the resulting time path of environmental quality was also discussed by Schumacher and Zou (2008) who show that pollution perception may change the dynamics qualitatively and lead to intergenerational inequity.

In order to analyze these arguments, we ascribe the environmental externality to partial perception of the individual impact on environmental quality corresponding to partial rivalry in congestion models, see Glomm and Ravikumar (1994), Fisher and Turnovsky (1998) or Eicher and Turnovsky (2000). Individuals recognize environmental quality to be influenced in part by themselves and in part by the rest of the society. Consequently, they only feel partially responsible for the level of pollution, and this partial responsibility may increase in the process of economic growth. European citizens e. g. are shown to undertake more environmentally-friendly actions if they are highly educated and well-informed about the environment (see European Commission 2011, p. 29). Another example is the rapidly increasing demand for organic products in most industrialized countries.

We distinguish two possible impacts of economic development on green attitude. First, wealth is an important determinant of individual attitude towards the environment. Richer nations can spend more on environmental education, richer individuals are able to spend more on green consumption. Hence green attitude will strengthen with an increase in wealth. The second determinant we regard is pollution itself. As environmental quality decreases, individuals will be more concerned with environmental issues and hence care more about the environment. For example, directly after the Fukushima nuclear accident a great majority emerged in favour of a switch to green energy, combined with a noticeable increase in the willingness to pay. People were not only more concerned about the environment, but they indeed changed their behavior. The demand for green electricity increased rigorously after the Fukushima accident.

We analyze the interdependence between green attitude and economic and environmental development. The individual attitude towards the environment determines the extent of the negative externality and therefore accumulation and abatement decisions. Capital accumulation and environmental quality in turn determine the evolution of green attitude. The resulting dynamics are complex. Pollution level and capital growth rate in principle decrease monotonically during the growth process and eventually converge to their optimal levels. Since capital accumulation enhances green attitude, the externality diminishes in the transition process and so does the gap between dynamic equilibrium and sustainable social optimum. Convergence will be faster, if the impact of capital on green attitude is stronger. Nevertheless, the implications of pollution determining green attitude are strictly different. Individuals will behave more environmentally friendly if pollution is high. Hence, whenever pollution decreases in the growth process due to increased abatement effort, green attitude will diminish. This effect may increase capital growth in the transition process and decelerate convergence to the steady state.

Externalities associated with environmental goods typically cause suboptimally high economic growth in dynamic market equilibrium. Brock and Taylor (2005) or Xepapadeas (2005) provide comprehensive overviews. The environmental externality must be internalized in order to realize a social optimal time path. There is a wide literature on environmental policy in endogenous growth models (see e. g. Stokey (1998) for tax and voucher schemes, Grimaud (1990) or Ono (2002) for pollution permits).[1] However, our focus is different. We show that endogenization of environmental externalities changes important features of dynamic market equilibrium, which in turn have do be regarded in order to evaluate environmental policy measures correctly. Of course, future work requires to analyze both problems in an integrated setting.

After the presentation of the assumptions in Sect. 2 we analyze the dynamic equilibrium in Sect. 3. Section 4 discusses the endogenous determination of green attitude. If green attitude gains importance throughout the growth process due to increasing wealth (Sect. 4.1), the equilibrium growth path converges to the sustainable growth path. If instead increasing pollution is the determinant for individual perception of environmental quality (Sect. 4.2), we show that the steady state pollution level as well as steady state growth remain suboptimally high. Section 4.3 explains the complex dynamic structure when both increasing wealth and pollution jointly determine green attitude. Section 5 concludes.

2 The Model

2.1 Environmental Quality and Green Attitude

There is evidence that the extent of environmental externalities and free rider behavior changes in time. For example, all but 5 % of European citizens consider the protection of the environment as important to them personally (European Commission 2014 question QA1), as displayed in Fig. 1a. Furthermore, a great majority of Europeans think that it should be done more for environmental quality, see Fig. 1b. A usual outcome concerning externalities is that 77 % of the respondents think that corporations and industry should do more to protect the environment. Correspondingly, 72 % (56 %) answer that the national governments (the European Union) don't do enough to use natural resources efficiently. But astonishingly, 65 % of the informants feel that the individuals themselves should behave more environmentally friendly.

In order to analyze the interdependence between environmental quality, individual awareness of environmental issues and economic development, we consider the growth path

[1] More recently, there was a shift of emphasis on human capital and R&D: Grimaud and Tournemaine (2007) as well as Pautrel (2012) work on the growth impact of environmental policy in corresponding endogenous growth settings.

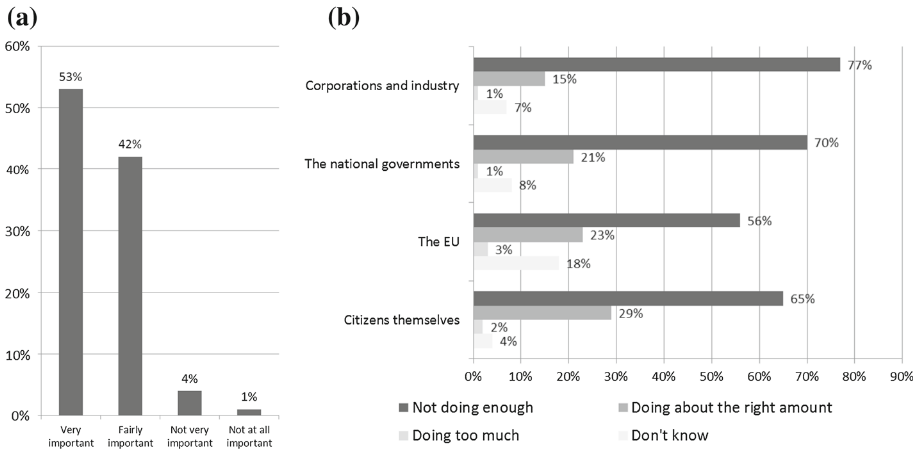

Fig. 1 Green attitude; based on questions in Special Eurobarometer 416, European Commission (2014). **a** "How important is protecting the environment to you personally?"; question QA1. **b** "In your opinion, are each of the following currently …doing too much, …doing about the right amount, or …not doing enough to use natural resources efficiently?"; question QA16

of an economy in which environmental pollution results from production of the homogenous consumption good. Environmental quality can be improved by abatement expenditure. Bretschger and Smulders (2007) show based on the general formulation $P = P(K, C, E)$ with capital, K, consumption, C, and abatement, E, that a balanced growth path with constant and equal growth rates of all macroeconomic variables will only be compatible with a constant pollution level, if pollution can be specified as $P = P(K/E, C/E, 1)$. In the following, we focus on the capital stock as the source of environmental damage.[2] Smulders and Gradus (1996) demonstrate that a sustainable growth path (as represented by a non-increasing level of pollution together with non-decreasing per-capita income, see e. g. Eriksson (2013, p. 147) or for recent and enlightening overview Bretschger (2015 ch.8)) may only be achieved if the pollution elasticity of capital does not exceed the pollution elasticity of environmental expenditure. We apply this result by assuming without a loss of generality identical elasticity that equals unity. More concretely, pollution in our model emerges according to $K(t)/E(t)$.

Green attitude is captured by the parameter δ which indicates that individuals perceive their influence on pollution only partially. In other words, the individuals do not realize the entire impact of their economic activity on the resulting pollution level. A related approach to pollution perception can be found in Schumacher and Zou (2008)[3]. The partial perception induces an external effect which ends up in a suboptimally high equilibrium level of pollution. Environmental pollution is perceived by the individuals according to the function

$$P(t) = \left(\frac{K(t)}{E(t)}\right)^{\delta} \left(\frac{k(t)}{e(t)}\right)^{1-\delta}, \qquad 0 \leq \delta < 1 \tag{1}$$

where K and E denote the aggregate levels of capital and expenditure for environmental protection; k and e are the respective individual variables. Assuming homogeneity of individuals,

[2] Due to linear production technology defined later in Eq. (6), the interdependency between pollution and capital stock is equivalent to pollution out of production.

[3] In Schumacher and Zou (2008) individual perception of pollution is parametrized, too, and can differ from actual pollution. Yet in their paper, misperception refers to pollution stock and flow, not on the individual impact on pollution.

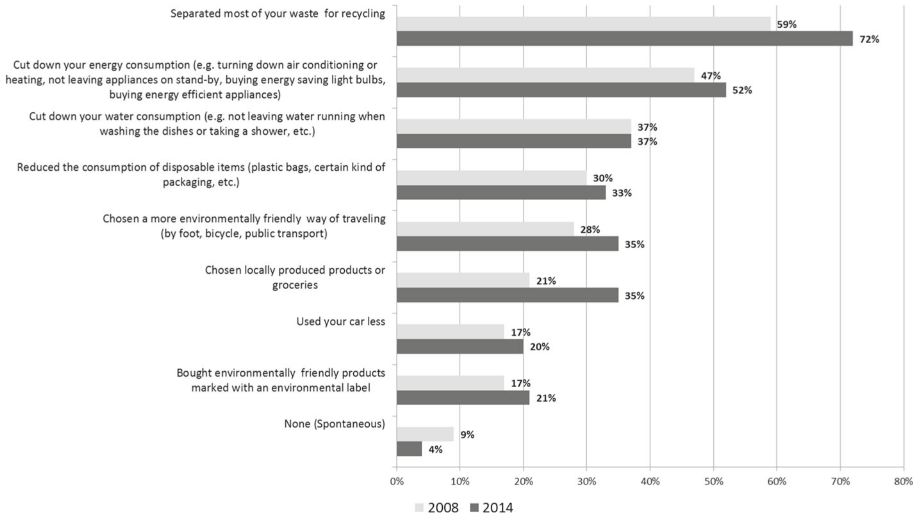

Fig. 2 "Have you done any of the following during the past month for environmental reasons?"; European Commission (2008, question QB12), European Commission (2014, question QA11)

the aggregate ratio K/E and the individual ratio k/e coincide, hence in equilibrium perceived pollution equals actual pollution $P(t) = K(t)/E(t)$. With this respect our approach to pollution perception differs from the one of Schumacher and Zou (2008). In our model, individuals are affected by actual pollution. But for individual decisions, they use the perception function of pollution (1). Due to missing (or partial) rivalry in environmental quality, the impact of individual activities on aggregate pollution is limited. Nevertheless, there is some perceived impact on pollution which individuals take into account.

The parameter δ denotes the share of pollution that is perceived as being exogenous to the individual's decision. Thus, $\delta = 0$ reflects the absence of any externality, i. e. the individuals perceive the entire (negative) impact of their actions on the resulting pollution level correctly. If, in contrast, δ is close to unity, the individuals perceive their own impact as atomistic and thus negligible.[4] Hence, an environmental externality arises whenever δ is positive. Then the influence of individual decisions on environmental quality is underestimated. A related argumentation can be found in Eriksson (2004) who demonstrates that individual preferences for environmentally friendly goods lead to a partial internalization of externalities. An improvement of green attitude hence corresponds to a decline in δ.

In reality, individuals show free rider behavior, but they don't exclusively free ride. To some extent they act environmentally friendly. There are several actions the European citizens execute due to environmental reasons, see Fig. 2. First of all, individuals separate waste (72 % of respondents). But they also cut down their energy consumption (52 %) and they even use their car less (20 %) in order to contribute to the improvement of environmental quality. Hence, individuals do not only understand a relationship between individual decisions and

[4] Alternatively one might interpret $1 - \delta$ as degree of rivalry for environmental pollution. This is analogous to the presentation of congestion effects in the context of public goods (compare e.g. Edwards 1990; Glomm and Ravikumar 1994; Turnovsky 2000 chap. 13). Most environmental goods are characterized by partial rivalry, i.e. they are described by $1 > \delta > 0$. Organic food, e.g., reduces individual pollution loads. This represents a kind of consumption rivalry. At the same time, the production of organic food also reduces pollution loads of the entire cultivable land. This benefits the other producers equally, i.e. there is no rivalry. This interpretation is applied in Soretz (2007).

aggregate pollution, but they perceive an individual impact on pollution and they consider the individual impact on pollution within their decisions. In the terminology of our assumptions, this means that the perception parameter δ indeed is below unity. Moreover, the number of European citizens who act environmentally friendly in order to help towards less pollution increases in time, as impressively shown in Fig. 2. Again transferred into our model, this means that green attitude improves and the perception parameter δ decreases in time.

Important determinants of the evolution of green attitude are education and income. Within the Special Eurobarometer, respondents were asked "As an individual, you can play a role in protecting the environment in your country?". Individuals estimate their influence on environmental protection the higher the more educated they are and the higher their personal income (see European Commission 2011 question QB 14.1, p. 20). With longer education time individuals know more about the impact of economic decisions on environmental quality. With increasing aggregate income usually the average education level enhances, and with increasing individual income people are able to behave more environmentally friendly. Moreover, people with higher income are more concerned with environmental problems, as e. g. described by Glaeser (2014). Glaeser emphasizes that the correlation between GDP and "... viewing global warming as a [personal] threat ... could also be explained by a more robust market for ideas in wealthier countries, in that their citizens feel free to express thoughts and debate issues without fear of repercussions from the government" (see Glaeser 2014, p. 210).

Another essential factor of individual environmental perception is environmental quality on its own. As long as the pollution level is low, individuals do not care about the impact of their actions on environmental quality but only consider their impact on the resulting consumption path. As pollution increases, the negative impact of capital accumulation on environmental quality becomes visible and thus fosters environmental awareness of the individuals. As also described by Schumacher (2009) green attitude will be more likely if the pollution level is high. The environmental consequences of economic decisions are more obvious, hence green attitude will enhance. For example, the survey underlying the Eurobarometer 365, (European Commission 2011) was carried out in april and may 2011, in direct succession of the Gulf of Mexico oil spill and the Fukushima nuclear accident. As a consequence, man-made disasters followed by water pollution were mentioned most freqently in 2011 to provoke the biggest effects of environmental change (see European Commission 2011, p. 14). Even more relevant, after the Fukushima accident, in German cities between 80.7 % (Leipzig) and 93.3 % (Hamburg) of households who changed the supplier of electric energy were interested in a change to green electricity. Before the Fukushima accident the corresponding quantities were 53.6 % (Leipzig) and 52.8 % (Hamburg) (see Süddeutsche Zeitung 2011 No. 93, p. 17).

In what follows we assume that green attitude is determined by economic development as well as by the pollution level as illustrated in fig. 3. The perceived impact of individual activity on environmental pollution is positively linked to increasing wealth, k. For less developed economies, the perception parameter δ is high and decreases throughout the growth process. This is a shortcut for the effort in environmental education, the possibilities for green consumption, larger freedom of expression and so on. Second, green attitude is positively linked to increasing pollution, P. Given low pollution levels, P, the perception parameter δ will be high and decreases with a rise in pollution. Formally spoken, we assume

$$\begin{aligned} \delta = \delta(k, P) \quad \text{with} \quad & \delta_k \leq 0, \delta_{kk} \geq 0, \quad \delta_P \leq 0, \delta_{PP} \geq 0 \\ & \delta(k_0, P_0) < 1, \lim_{k\to\infty} \delta = 0, \lim_{P\to\infty} \delta = 0 \end{aligned} \tag{2}$$

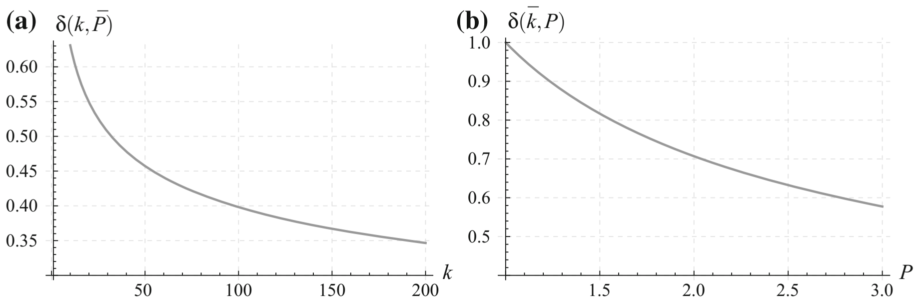

Fig. 3 Evolution of green attitude. **a** Green attitude determined by wealth, $\delta(k, \bar{P})$. **b** Green attitude determined by pollution, $\delta(\bar{k}, P)$

Moreover, we work with constant elasticities of green attitude with respect to capital, ξ_k, and with respect to pollution, ξ_P, with

$$\frac{\partial \delta}{\partial k}\frac{k}{\delta} = \xi_k \leq 0 \qquad \frac{\partial \delta}{\partial P}\frac{P}{\delta} = \xi_P \leq 0 \tag{3}$$

Constant elasticities will facilitate the description of the dynamic equilibrium as well as numerical analysis without loss of generality.[5]

2.2 Further Assumptions

Environmental pollution affects individual decisions as it induces dis-utility. We assume a continuum of infinitely lived individuals who maximize intertemporal utility. Intertemporal utility, however, might also be interpreted in a model of overlapping generations where parents are altruistic with respect to their own children—an assumption that is especially plausible in the context of environmental quality which frequently only becomes prevalent for subsequent generations. Intertemporal utility is assumed to be additively separable across time and is given by

$$U = \int_0^\infty \exp(-\rho t) u(c, P)\, dt \tag{4}$$

The parameter $\rho > 0$ denotes the constant rate of time preference.[6] Especially in the context of sustainability, the choice of a positive rate of time preferences has been critically discussed already by Ramsey (1928, p. 543) who stated that discounting future utility reflects "…a practise which is ethically indefensible and arises merely from the weakness of the imagination." The assumption of a positive rate of time preference, however, within this paper is chosen since we intend to describe the real development of an economy and not a socially desired time path. The positive discount rate is supported by empirical studies that show that the real rate of return on capital exceeds the growth rate of an economy significantly.

Instantaneous utility, $u(c, P)$, is characterized by a constant intertemporal elasticity of substitution, ε, as well by an intratemporal elasticity of substitution between consumption and pollution equal to unity. Notice that both are knife-edge assumptions which reflect necessary preconditions for the existences of a sustainable growth path with a constant level of pollution

[5] For numerical analysis, we specify individual awareness as $\delta(k, P) = k^{\xi_k} P^{\xi_P}$.

[6] The time preference rate could also be assumed to decrease in green attitude. In this paper, we assume ρ independent from green attitude because we focus on the implications of green attitude on free riding behavior and the corresponding changes in the negative externality rather than on short-sightedness.

(compare e.g. Smulders and Gradus 1996). Thus the intratemporal utility function is given by

$$u(c, P) = \frac{(cP^{-\gamma})^{1-1/\varepsilon}}{1-1/\varepsilon}, \qquad 0 < \varepsilon < 1, \quad \gamma > 0. \tag{5}$$

The additional assumption that the intertemporal elasticity of substitution has to fall short of unity results from unequivocal empirical studies (e.g. Hall 1988; Epstein and Zin 1991). The parameter γ represents the relative impact of dis-utility out of environmental pollution.

The linear production of the homogenous consumption good is given by

$$f(k) = Ak, \qquad A > 0. \tag{6}$$

The only productive input is capital that shall be broadly interpreted to include, e.g. human capital. In order to focus on environmental externalities, we abstract from further externalities within consumption good production.

3 Equilibrium Growth and Environmental Quality

3.1 Dynamic Optimization

In the following we analyze the dynamic market equilibrium and focus on the implications of green attitude. The resulting growth rate is unequivocally smaller than in an economy without pollution, i.e. with clean technology.[7]

To determine the growth equilibrium the individual maximizes intertemporal utility subject to private capital accumulation[8]

$$\begin{aligned} \max_{c,e,k} \quad & U = \int_0^\infty \exp(-\rho t) u(c, P)\, dt \\ \text{s. t.} \quad & \dot{k} = Ak - c - e \end{aligned} \tag{7}$$

which gives the current-value Hamiltonian

$$\mathcal{H} = \exp(-\rho t) u(c, P) + \lambda (Ak - c - e) \tag{8}$$

The individual decides on consumption, c, abatement activity, e, and on capital accumulation, k. Pollution is perceived to be determined according to (1) and green attitude evolves as assumed in (2). The resulting first-order conditions are

$$\frac{\partial \mathcal{H}}{\partial c} = \exp(-\rho t) u_c - \lambda = 0 \tag{9}$$

$$\frac{\partial \mathcal{H}}{\partial e} = -\exp(-\rho t) u_P \left(1 - \delta + \delta_P P \left(\ln\left(\frac{K}{E}\right) - \ln\left(\frac{k}{e}\right)\right)\right) \frac{P}{e} - \lambda = 0 \tag{10}$$

$$\frac{\partial \mathcal{H}}{\partial k} = \exp(-\rho t) u_P \left(1 - \delta + k\delta_k \left(\ln\left(\frac{K}{E}\right) - \ln\left(\frac{k}{e}\right)\right)\right) \frac{P}{k} + \lambda A = -\dot{\lambda} \tag{11}$$

[7] This result is closely related to the assumption of a one-sector economy. If there were, e.g. an additional sector for human capital that accumulates without pollution, pollution had neither impact on the optimal nor on the equilibrium growth rate (e.g. Gradus and Smulders 1993) Besides, it is shown that the equilibrium environmental quality is the lower, the lower is the extent of environmental pollution that individuals perceive as being the outcome of their own activity. Nevertheless, the dynamics resulting from the interdependence between capital accumulation, green attitude and pollution are more complex.

[8] In the following, we use the notation $\dot{x} = \partial x / \partial t$ and $\hat{x} = \dot{x}/x$.

Equalizing (9) and (10) together with the equilibrium feature $K/E = k/e$ leads to the (individually) optimal allocation of consumption and environmental expenditure

$$\frac{e}{c} = \gamma(1-\delta) \tag{12}$$

The ratio between expenditures in environmental protection, e, and consumption, c, is determined by the environmental preferences, γ, and attitude towards the environment, δ. The higher the perceived dis-utility out of pollution, the higher is relative abatement expenditure. This already points up to the central impact of individual perception of environmental quality: The higher the share δ of environmental quality, which seems to be the outcome of the aggregate (and thus not manipulable through individual behavior), the lower is the individually perceived utility out of environmental expenditure and thus the lower is the corresponding budget invested in environmental protection.

Capital growth results directly from capital accumulation given in (7) together with optimal abatement activity (12)

$$\hat{k} = A - \frac{c}{k} - \frac{e}{k} = A - (1 + \gamma(1-\delta))\frac{c}{k} \tag{13}$$

Utilizing $\dot{\lambda}$ derived from (9) together with (11) provides the Keynes-Ramsey rule which describes the growth rate of consumption

$$\hat{c} = \varepsilon\left(A - \gamma(1-\delta)\frac{c}{k} - \rho - \gamma(1-1/\varepsilon)\hat{P}\right) \tag{14}$$

Private capital return A is reduced by environmental damage, indicated by abatement activity $\gamma(1-\delta)c/k$. Along the equilibrium growth path, the abatement ratio, e/k, and thus the growth rate of pollution, $\hat{P}$, are endogenously determined. In the following, we will restrict our analysis to parameter settings which enable for ongoing growth. In particular, capital productivity has to be sufficiently large, $A > \rho(1 + \gamma(1-\delta))$.[9]

Concerning the evolution of environmental quality, one has to bear in mind that following (12) abatement activity increases with expenditure for consumption goods, because consumption and environmental quality are complementary arguments within the utility function (5). At the same time, attitude towards the environment will change within the growth process, additionally increasing abatement expenditure.

$$\hat{P} = \hat{k} - \hat{e} = \hat{k} - \widehat{(1-\delta)} - \hat{c} \tag{15}$$

Since green attitude evolves depending on wealth and environmental quality, definition of the elasticities ξ_k and ξ_P given in (3) allows the representation

$$\widehat{(1-\delta)} = -\frac{\delta}{1-\delta}\hat{\delta} = -\frac{\delta}{1-\delta}(\xi_k\hat{k} + \xi_P\hat{P}) \tag{16}$$

Note that both elasticities are negative and constant by assumption. Hence, if capital or pollution increase, $(1-\delta)$ will rise, too. This mirrors our assumptions about green attitude: increasing wealth allows for more environmental education, and more pollution increases environmental awareness, both reducing the part δ of pollution which seems to be unrelated with individual economic decisions.

Economic growth and environmental quality are dynamically interdependent. In order to disentangle the various occurring effects, first we analyze the case of exogenous and constant attitude towards the environment as a reference situation. Subsequently we show

[9] This condition will become obvious as soon as dynamic equilibrium is solved, see (18).

that the impact of wealth on green attitude reduces capital growth and induces an adjustment towards the sustainable pollution level. Afterwards we focus on the impact of pollution on green attitude which can be shown to hamper the adjustment towards the optimal growth path.

3.2 Exogenous Attitude Towards the Environment

If individual attitude towards the environment is exogenously given and constant, $\delta = \bar{\delta}$, the economy will immediately realize steady state growth. It can easily be seen from Eq. (12) that with invariant attitude towards the environment (hence $\bar{\delta}_k = \bar{\delta}_P = 0$) the equilibrium growth path implies that environmental expenditures and consumption grow at the same and constant rate.[10] In this case, the macroeconomic variables all grow at the same rate thereby leading to constant levels of abatement ratio, e/k, and pollution, P. The growth rate then just differs from the one in an economy which produces without pollution, $\varepsilon(A - \rho)$, by the term $-e/k$, or put differently, equilibrium growth is unequivocally smaller if pollution arises: pollution which is linked to capital accumulation reduces the effective marginal product of capital and thus the economy's equilibrium growth rate.

Combining abatement activity (12), capital growth (13) and consumption growth (14) allows for the explicit determination of the pollution level and the growth rate

$$P(\bar{\delta}) = \frac{1 + (1 - \varepsilon)\gamma(1 - \bar{\delta})}{\gamma(1 - \bar{\delta})(\varepsilon\rho + (1 - \varepsilon)A)} \tag{17}$$

$$\hat{k}(\bar{\delta}) = \hat{c}(\bar{\delta}) = \frac{\varepsilon(A - (1 + \gamma(1 - \bar{\delta})\rho))}{1 + (1 - \varepsilon)\gamma(1 - \bar{\delta})} \tag{18}$$

The more pronounced environmental preferences (i.e. higher γ) the lower is the equilibrium growth rate. Pollution induces a dis-utility which reduces capital productivity and thus also private capital accumulation. This effect is magnified if the perception parameter, $\bar{\delta}$, decreases which implies that a bigger part of pollution is ascribed to individual decisions. The impact of perceived pollution on individual accumulation is captured within the term $\gamma(1 - \bar{\delta})$. Incomplete perception of the impact of individual decisions on the pollution level, i.e. $\bar{\delta} > 0$, results in a suboptimally high growth rate. Part of the negative effect of capital accumulation via pollution on intertemporal utility is neglected which leads to an overestimation of capital productivity. Consequently equilibrium growth is suboptimally high. Complete knowledge about the relationships between individual and aggregate dimensions as regards the evolution of pollution ($K/E = k/e$ and thus $P = k/e$ which is equivalent to the polar case $\delta = 0$) would result in optimal pollution level and optimal growth

$$P^* = \frac{1 + (1 - \varepsilon)\gamma}{\gamma(\varepsilon\rho + (1 - \varepsilon)A)} \tag{19}$$

$$\hat{k}^* = \hat{c}^* = \frac{\varepsilon(A - (1 + \gamma)\rho)}{1 + (1 - \varepsilon)\gamma} \tag{20}$$

As expected, equilibrium growth (18) exceeds optimal growth (20) and equilibrium pollution (17) exceeds optimal pollution (19) confirming the well-known impact of a negative externality in capital accumulation on the growth rate in market equilibrium. Green attitude determines the deviation of the market equilibrium from the social optimum.

[10] This result is due to the specification of the pollution function, as shown in Bretschger and Smulders (2007) and the intratemporal elasticity of substitution which equals unity, as shown in Smulders and Gradus (1996).

Indeed, environmental preferences and the attitude towards the environment jointly influence the effective intertemporal elasticity of substitution as well as the effective rate of time preference. The effective intertemporal elasticity of substitution, $\varepsilon/(1+(1-\varepsilon)\gamma(1-\bar{\delta}))$, is lower than ε due to environmental preferences ($\gamma > 0$) and due to environmental awareness ($\bar{\delta} < 1$). The lower the effective intertemporal elasticity of substitution, the lower is the growth rate for any given private capital return, A. Additionally, the effective rate of time preference, $(1+\gamma(1-\bar{\delta}))\rho$, is higher than ρ due to pollution and the awareness of pollution. This reinforces the growth diminishing impact described just before.

The suboptimally high level of pollution in dynamic equilibrium could motivate to internalize the pollution externality via a sophisticated tax-transfer-system. Within the provided framework this could be done e. g. via the implementation of a tax on pollution or capital returns respectively together with a subsidy on environmental protection. Since in the underlying model the environmental policy measures work in the well-known way we forgo their analysis here.

However, at the same time this raises the question about the determinants of green attitude and it is quite implausible to assume that this characteristic remains constant as an economy evolves. We will now come back to the assumption that green attitude is determined by wealth and by pollution as given in (2). Hence dynamics will be more complex. Equation (12) already shows that with endogenous attitude towards the environment the growth rates of abatement, e, and consumption, c, will differ. When green attitude gains importance, $(1-\delta)$ increases and environmental expenditure grows faster than consumption. Hence, the economy cannot realize steady state immediately.

The following part analyzes the impact of endogenous environmental attitude on aggregate growth and the evolution of the pollution level. In doing so, we explicitly focus on two different initial points: We begin with a situation in which environmental perception is solely linked to increased welfare (Sect. 4.1). In Sect. 4.2 we focus on the impact of pollution on green attitude. Then we combine the arguments in Sect. 4.3.

4 Endogenous Green Attitude

If environmental attitude is determined by wealth or pollution, the amount of the pollution externality becomes endogenous. Hence, the extent to which the environmental consequences of individual decisions is taken into account, may change in time, depending on the development of the economy. In particular, if wealth has influence on green attitude, pollution and capital growth are no longer constant.

The dynamics of the interdependent system of capital growth, consumption growth and abatement activity can be described as follows (and as given in fig. 4). Capital growth can directly be taken from equation (13) and is positive if the consumption ratio, c/k, is sufficiently small, as derived in (28) in the appendix. Hence, below the $\hat{k} = 0$ locus capital growth is positive and above the locus it is negative. The dynamics of the consumption ratio are given in (32). The evolution is unstable: Below the $\widehat{c/k} = 0$ locus the consumption ratio decreases and above it increases. Together, the phase diagram displayed in Fig. 4 applies. The detailed derivation is given in the appendix.

If there is an impact of capital on green attitude, both isoclines are convex and falling functions in k, see Fig. 4a and the derivation in the appendix. There exists a unique saddle path which is located below the locus of the constant consumption ratio. The saddle path is a convex and declining function in k and for an infinitely large capital stock it converges to the

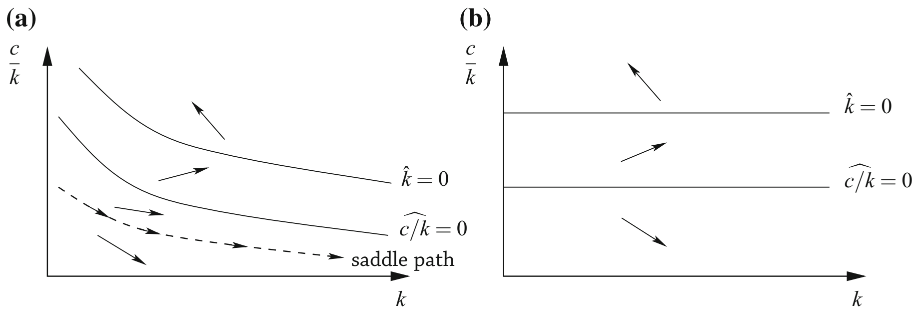

Fig. 4 Saddle path dynamics. **a** Impact of capital on green attitude $\delta_k < 0, \delta_P \leq 0$. **b** No impact of capital on green attitude $\delta_k = 0, \quad \delta_P \leq 0$

locus of the constant consumption ratio. Along the saddle path, capital increases and therefore environmental perception enhances. δ decreases indicating that individuals take a larger part of the environmental consequences of their decisions into account. Hence, consumption ratio and pollution decrease in time. Nevertheless, as the saddle path cannot be determined explicitly, we partially are restricted to numerical analysis.

If only pollution determines green attitude, both isoclines are flat lines as displayed in Fig. 4b and also derived in the appendix. In this case, the economy realizes a balanced growth path with constant and equal growth rates of consumption, abatement and capital from the beginning on. The saddle path coincides with the $\widehat{c/k} = 0$ locus.

Whenever the growth rate of consumption is smaller than capital growth, the consumption ratio will decrease in time. Hence, abatement tends to decrease, too, increasing the pollution level. At the same time, capital growth will enhance green attitude, if it has an impact on it. Therefore, abatement tends to increase and if the growth rate of abatement expenditure exceeds capital growth, pollution decreases. In order to disentangle the various effects we start with the assumption, that environmental awareness is exclusively determined by capital.

4.1 Green Attitude Determined by Wealth

In what follows we assume that the individual attitude towards the environment may be explained by the economic development, i.e. the perceived impact of individual activity on environmental pollution is positively linked to increasing wealth, k. This might be due to increased effort in environmental education or because environmentally friendly behavior is a kind of luxury good. Concerning the perception function $\delta(k)$ we assume $\delta_k < 0$ and $\delta_{kk} > 0$, with $\delta(k_0) < 1$ and $\lim_{k\to\infty} \delta = 0$ (as given in Fig. 3a). Furthermore, we abstract from any impact of pollution on environmental awareness, that is $\delta_P = \xi_P = 0$. The evolution of the macroeconomic variables throughout the transition process may be derived from equations (28) and (32) by setting $\xi_P = 0$. The resulting dynamic equilibrium still is saddle point stable as displayed in Fig. 4a.

As the saddle path cannot be determined explicitly we cannot show the evolution of capital growth and pollution level on the equilibrium transition path. Nevertheless, it is possible to identify their main characteristics. Consider pollution with optimal abatement according to (12) and capital growth as given in (13)

$$P = \Big(\gamma \underbrace{(1-\delta)}_{\uparrow} \underbrace{\frac{c}{k}}_{\downarrow}\Big)^{-1} \qquad \hat{k} = A - (1 + \gamma \underbrace{(1-\delta)}_{\uparrow})\underbrace{\frac{c}{k}}_{\downarrow} \tag{21}$$

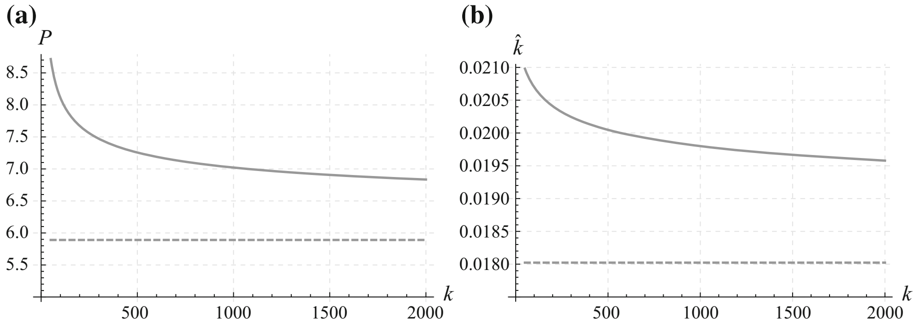

Fig. 5 Evolution of pollution and capital growth; *solid lines*: $c/k = \mu_c$; *dashed lines*: socially optimal levels; parameters: $\varepsilon = 0.1$, $\rho = 0.05$, $A = 0.4$, $\gamma = 0.8$, $\xi_k = -0.2$. **a** Pollution. **b** Capital growth

It is straightforward that two opposing effects emerge. The consumption ratio, c/k, decreases along the saddle path. Ceteris paribus a decline in consumption increases capital growth and decreases abatement. However green attitude enhances simultaneously, hence δ decreases. Ceteris paribus this decreases capital growth and increases abatement activity.

Pollution as well as capital growth can be shown to decrease unambiguously on the transition path: the impact of enhanced environmental awareness dominates the impact of decreased consumption and abatement. The argument runs as follows: First, we show that pollution would decrease if the individuals chose the consumption ratio $c/k = \mu_c$. Second, we compare pollution on the saddle path with the previous result. As discussed in the appendix, the sign of the slope of μ_c cannot be determined unequivocally. Anyway for all reasonable parameter settings,[11] capital growth and pollution level for $c/k = \mu_c$ are decreasing as displayed in Fig. 5.

In the market equilibrium, individuals do not choose the consumption ratio $c/k = \mu_c$, instead the economy follows the saddle path. Since the saddle path is situated below the $\widehat{c/k} = 0$ locus but converges to this isocline for infinitely large capital, the slope of the saddle path is smaller (in absolute values). Hence the consumption ratio on the saddle path is smaller than μ_c and decreases more slowly. Consequently, the impact of decreasing consumption and abatement on pollution and capital growth is less intense. Considering Eq. (21) again shows that the impact of the enhanced green attitude will dominate even more on the saddle path: Pollution and capital growth will both be larger on the saddle path than in the $c/k = \mu_c$ case and decrease faster.

The reason is that with increasing wealth a bigger share of pollution is attributed to own individual decisions (i.e. decreasing δ), and thus the perceived impact of ongoing capital accumulation on pollution increases. This effect dominates the impact of the decreasing consumption ratio. A growing economy will thus always be characterized by a decreasing pollution level since stronger attitude towards the environment (due to $\xi_k < 0$) makes abatement grow faster than the capital stock.

[11] We verified that the displayed results do not change in the ranges $0 < \rho \leq 0.2$, $0 < \varepsilon \leq 0.9$, $0.1 \leq A \leq 4$, $-5 \leq \xi_P \leq 0$, $-5 \leq \xi_k \leq 0$. Nevertheless, where necessary we set the parameters as follows. Since we use the Ak technology with a broad measure of capital, we choose the capital coefficient relatively small and set $A = 0.4$. With $\gamma = 0.8 < 1$ pollution is decided to be less important for utility than consumption. The rate of time preference is set to $\rho = 0.05$ and intertemporal substitution to $\varepsilon = 0.1$, which is a quite small value, but results in regular values for steady state capital growth around 1.5–2 %. The impact of wealth or pollution on green attitude are set to relatively small values $\xi_k = -0.2$ and $\xi_P = -0.2$ because we believe that individual behavior will not change rapidly.

Given ongoing growth of capital, environmental awareness enhances ($\delta_k < 0$) and the perception parameter finally converges towards zero, $\lim_{t\to\infty} \delta(k) = 0$. As a consequence, all individuals finally consider the entire impact of their decisions on environmental quality and all equilibrium values of consumption, pollution and growth converge to their respective optimal values

$$\lim_{t\to\infty} P = \frac{1+(1-\varepsilon)\gamma}{\gamma(\varepsilon\rho+(1-\varepsilon)A)} = P^* \tag{22}$$

$$\lim_{t\to\infty} \hat{k} = \lim_{t\to\infty} \hat{c} = \frac{\varepsilon(A-(1+\gamma)\rho)}{1+(1-\varepsilon)\gamma} = \hat{k}^* \tag{23}$$

It can be seen from Eq. (36) that for $\delta \to 0$ the $\widehat{c/k} = 0$ locus converges to a constant steady state level which coincides with the optimal consumption ratio. Hence in the steady state consumption and capital grow with the same rate. Inserting the steady state consumption ratio into (13) gives the steady state growth rate of capital (23) and the steady state pollution level (22).

The resulting level of environmental pollution will thus in the long run fall short of the equilibrium values presented in the last section with exogenous and constant environmental perception. The underlying reason for the convergence to the optimal values is that throughout the growth process knowledge and understanding for the relationships between capital accumulation, environmental protection and environmental quality increases. The environmental externality is internalized successively and the gap between market equilibrium and social optimum diminishes. Of course we have to admit that the convergence towards the optimal growth path is due to the assumption that individual responsibility for the environment eventually will become perfect, hence the negative environmental externality disappears completely. However, in a more realistic setting the externality will only diminish and not disappear entirely. Thus capital growth and pollution level will approximate their optimal levels but the deviation will persist.[12]

The transitional dynamics are crucially influenced by ξ_k, the extent to which an increase in wealth, k, enhances green attitude, δ. An increase in the impact of wealth on environmental awareness might be initiated for example by increasing the expenditures for environmental education. But it might also be due to lifestyle changes in favour of ecologically friendly goods if it gets more famous to show high wealth by green consumption. The consequences of a rise in ξ_k on transitional dynamics are displayed in the phase diagrams in Fig. 6. First, there is an immediate decrease in δ which corresponds to a prompt change in green attitude: Both isoclines move downwards, hence the saddle path indicates a lower individually optimal consumption ratio. Moreover, the shape of both isoclines changes. With higher ξ_k convergence to the socially optimal steady state is faster. An approximation to the optimal levels of consumption ratio, pollution level and capital growth already takes place for smaller capital stock. There is less need for economic development as a base for taking environmental issues into concern.

To summarize the results derived so far: The economy converges against the sustainable growth path if increased wealth enhances individual attitude towards the environment. Capital growth as well as the pollution level remain suboptimally high in the transition process and diminish until green attitude becomes complete and the negative externality vanishes entirely. The speed of convergence is mainly influenced by the impact of wealth on environmental

[12] The dynamics would not change substantially for a positive lower bound of δ. Nevertheless, we keep the assumption $\lim_{k\to\infty} \delta = 0$ in order to simplify numerical analysis.

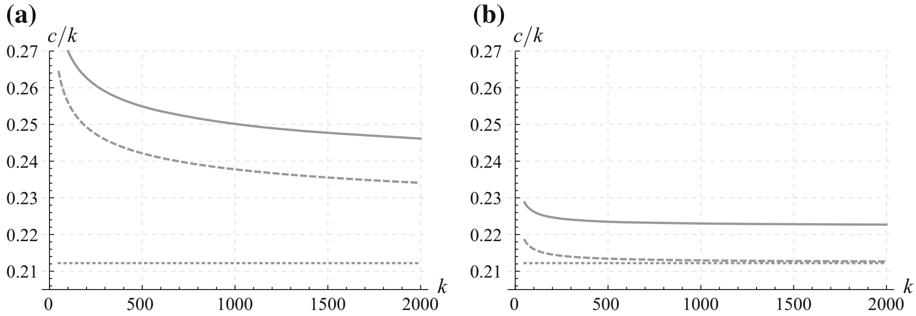

Fig. 6 Transitional dynamics with different impact of wealth; *solid lines*: $\hat{k} = 0$; *dashed lines*: $\widehat{c/k} = 0$; *dotted lines*: socially optimal c/k; parameters: $\varepsilon = 0.1$, $\rho = 0.05$, $A = 0.4$, $\gamma = 0.8$. **a** Low impact of wealth on green attitude, $\xi_k = -0.2$. **b** Higher impact of wealth on green attitude, $\xi_k = -0.7$

awareness. This immediately implies that any environmental policy should be complemented by policy means to accelerate individual sensitivity as regards green attitude.

4.2 Green Attitude Determined by Pollution

In this part we analyze the impact of pollution on green attitude. We focus on the argument that an increase in the pollution level makes the consequences of economic decisions on environmental quality more obvious and hence improves green attitude. As regards the perception function, $\delta(P)$, we assume that $\delta_P < 0$ and $\delta_{PP} > 0$, where $\delta(P_0) < 1$ and $\lim_{P\to\infty} \delta = 0$ (compare Fig. 3b). Additionally, at first we abstract from any impact of wealth on green attitude, that is $\delta_k = \xi_k = 0$.

With green attitude independent from the capital stock, the dynamic equilibrium evolves according to Fig. 4b. Consumption and capital grow with the same constant rate, because otherwise the economy would depart at all times farther from the steady state. Hence the individuals immediately choose the consumption ratio μ_c which stays constant in time. Moreover, there is a key difference in the equilibrium steady state as regards the evolution of abatement activity. According to (16) with $\xi_k = 0$ together with (15), pollution growth results in

$$\hat{P} = \hat{k} - \hat{e} = \hat{k} - (\widehat{1 - \delta(P)}) - \hat{c} = \frac{\delta}{1-\delta}\xi_P \hat{P} - \widehat{c/k} \quad \Rightarrow \quad \hat{P} = -\frac{\widehat{c/k}}{1 - \frac{\delta}{1-\delta}\xi_P} \tag{24}$$

It is straightforward that the pollution level will be constant if consumption and capital grow with the same rate. Hence, within the dynamic equilibrium $\hat{c} = \hat{k} = \hat{e}$ holds at each point of time. Consequently the economy at once reaches the steady state growth path without the necessity to pass through a transition process. The steady state is determined by the consumption ratio given in (32) with $\xi_k = 0$. Together with (12) and (13) pollution level and capital growth can be determined

$$P(\delta(P)) = \frac{1 + (1-\varepsilon)\gamma(1-\delta)}{\gamma(1-\delta)(\varepsilon\rho + (1-\varepsilon)A)} \tag{25}$$

$$\hat{k}(\delta(P)) = \frac{\varepsilon(A - (1 + \gamma(1-\delta))\rho)}{1 + (1-\varepsilon)\gamma(1-\delta)} \tag{26}$$

Equations (25) and (26) suggest that $\delta(P)$ can be determined uniquely in equilibrium. The pollution level depends on green attitude ($P = P(\delta)$) and green attitude depends on pollution

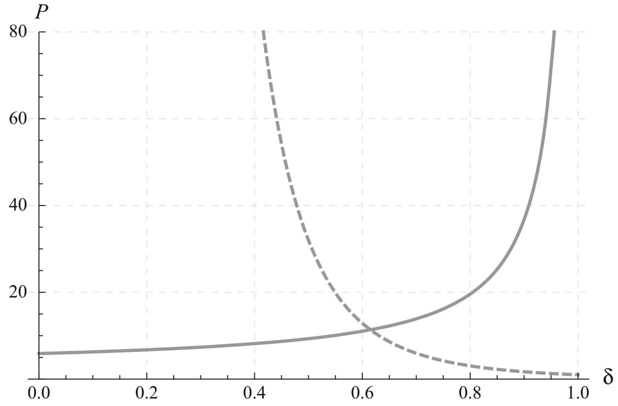

Fig. 7 Equilibrium attitude towards the environment; *solid line* $P(\delta)$ from (25), *dashed line* $\delta(P)$ given by assumption; parameters $\varepsilon = 0.1$, $\rho = 0.05$, $A = 0.4$, $\gamma = 0.8$, $\xi_P = -0.2$

($\delta = \delta(P)$). As given in (25) pollution is increasing in the perception parameter, $\partial P/\partial\delta > 0$. The perception parameter depends negatively on the pollution level, $\partial\delta/\partial P < 0$, by assumption. Hence, there is a unique and positive solution for equilibrium attitude towards the environment. Both functions are shown in Fig. 7. The equilibrium perception level is reached instantaneously. Nevertheless one can imagine an adjustment towards the equilibrium. If the economy starts with less green attitude (higher δ), individuals will take only a smaller part of influence on the environment into account. The corresponding pollution level will be higher, thus individuals will recognize their impact on the environment and green attitude is enhanced (decreasing δ).

The resulting equilibrium level of pollution will be the lower (and equilibrium green attitude the more pronounced), the stronger environmental preferences (higher γ), the higher the rate of time preference ρ or the higher capital productivity A. Stronger environmental preferences imply that dis-utility out of pollution gains importance, hence individuals give more weight on the environmental implications of their actions and behave more environmentally friendly. An increase in the rate of time preference, ρ, will decrease capital growth. Therefore equilibrium pollution decreases and equilibrium δ increases. An rise in productivity, A, will increase both capital growth and abatement activity. Equation (32) together with (12) show that the abatement ratio $e/k = \gamma(1-\delta)\mu_c$ is increasing in capital productivity. The income effect of increasing productivity on abatement activity dominates the growth increasing impact. Thus the equilibrium level of pollution decreases.

As already mentioned, the endogenous evolution of green attitude does not end up in the socially optimal growth path if perception is linked exclusively to environmental quality. In equilibrium, capital and environmental spending grow at identical rates. Then the pollution level remains unchanged without inducing any further impulses as regards perception. The economy remains at a suboptimal pollution level and a transition to a sustainable growth path, as derived in the last section where increasing wealth is accompanied by a more sensitive environmental perception, may not be derived.

With the underlying simple assumptions the economy will immediately realize the steady state values of growth and pollution as indicated in (25) and (26). Of course, one can imagine that in reality green attitude will not adjust immediately. Instead, there will be a process of

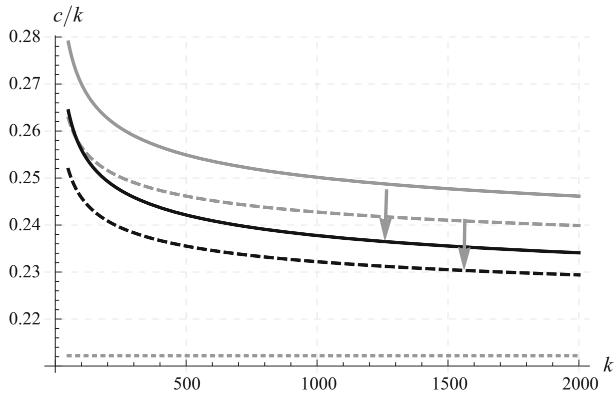

Fig. 8 Transitional dynamics with additional impact of pollution on green attitude; *solid lines*: $\delta = \delta(k)$ with $\xi_P = 0$, *dashed lines*: $\delta = \delta(k, P)$, *dotted line*: socially optimal c/k; *gray lines*: $\hat{k} = 0$, *black lines*: $\widehat{c/k} = 0$; parameters: $\varepsilon = 0.1$, $\rho = 0.05$, $A = 0.4$, $\gamma = 0.8$, $\xi_k = -0.2$, $\xi_P = -0.2$

strengthening attitude towards the environment. A process where green attitude reacts on the previous level of pollution and pollution in turn results from the current environmental awareness could induce a cyclical adjustment process which would take time. Nevertheless, such phenomena cannot be analyzed with the current version of the model, hence we let them for future research.

4.3 Green Attitude Determined Jointly by Wealth and Environment

Finally we come back to the general assumption that green attitude is determined by wealth and by pollution simultaneously, hence $\delta = \delta(k, P)$ with the assumptions concerning the derivatives imposed in (2). Equilibrium growth again is characterized by a decreasing consumption ratio according to a saddle path as displayed in Fig. 4a. The relevant $\hat{k} = 0$ and $\widehat{c/k} = 0$ loci are given in (28) and (32) respectively. Of course, with capital determining green attitude, we again see transitional dynamics. The change caused by the impact of pollution on environmental awareness is displayed in Fig. 8.

Because an increase in capital enhances environmental perception, the $\hat{k} = 0$ locus as well as the $\widehat{c/k} = 0$ locus are falling and convex functions in the consumption ratio, c/k. The gray curves represent the reference setting that only capital has an influence on green attitude. They are adopted as discussed in Sect. 4.1. The additional impact of pollution on green attitude is featured in the black curves. Both loci are moved downwards, hence the saddle path will unambiguously move downwards, too. The reason is obvious: green attitude will enhance if individuals reconsider their environmental awareness in view of pollution. Hence, δ will decrease and the individually chosen consumption ratio, c/k, is reduced.

Nevertheless, the consequences on pollution and capital growth are more complex, because the system of capital growth, pollution and green attitude is interdependent. In order to analyze the development of pollution, we first analyze pollution on the $\widehat{c/k} = 0$ locus and then argue that pollution on the saddle path is larger than on the $\widehat{c/k} = 0$ locus. The pollution level which is associated with the $\widehat{c/k} = 0$ locus, can be determined similar to the considerations in the last subsection. From $\widehat{c/k} = 0$ follows immediately that $c/k = \mu_c$ as given by (32). With (12) pollution results in $P = 1/(\gamma(1 - \delta)\mu_c)$ and is depicted in Fig. 9. The upward sloping dashed curve displays the pollution level associated with $\widehat{c/k} = 0$ in dependence of

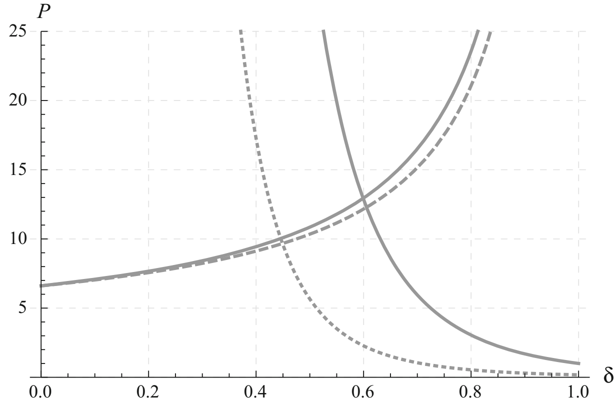

Fig. 9 Pollution level for $\widehat{c/k} = 0$; *solid lines*: $P(\delta)$ and $\delta(P)$ for $\xi_k = 0$, *dashed line* $P = 1/(\gamma(1-\delta)\mu_c)$, *dotted line* $\delta(k, P)$ from (2) with higher k ($k = 2$); parameters $\varepsilon = 0.3$, $\rho = 0.05$, $A = 0.4$, $\gamma = 0.8$, $\xi_k = -0.5$, $\xi_P = -0.2$

environmental perception, δ. Pollution increases in δ on this curve, as an increase in δ means that individuals take only a smaller part of the environmental consequences of their decisions into account. Hence, abatement activity decreases.

As a reference, the corresponding pollution level without impact of capital on green attitude also is given in Fig. 9. The solid upward sloping curve indicates the pollution level depending on environmental awareness for $\xi_k = 0$. Due to the impact of capital on green attitude, abatement activity is increased. The function moves downwards and $\xi_k < 0$ generates the dashed curve. Hence, if the individuals chose the consumption ratio $c/k = \mu_c$ the pollution level would decrease.

In fact, the economy will evolve along the saddle path which is located below the $\widehat{c/k} = 0$ locus. The consumption ratio chosen by the individuals is lower than μ_c. Abatement is decreased together with consumption since both are complementary goods, see (12). As a consequence, the pollution level (for any *given* environmental perception, δ) will be higher than indicated with the dashed curve in Fig. 9.

Moreover, the capital stock affects the equilibrium pollution level via green attitude as given in (2). Environmental awareness enhances with capital accumulation due to $\xi_k < 0$. The effect of capital endowment on the equilibrium pollution level is unequivocally negative, as displayed in Fig. 9. An increase in wealth enhances green attitude (δ decreases) which results in the shift of the function $\delta(k, P)$ to the left. Hence individuals give more weight on the environmental impact of their activities and reduce the equilibrium pollution level. The intersection point in Fig. 9 again shifts downwards. This process goes on until the steady state is reached, environmental awareness is complete ($\delta = 0$) and the optimal pollution level is realized. The curve $\delta(k, P)$ then intersects the curve $P(\delta)$ at the P-intercept of the latter.

There is not only the described impact of capital accumulation on pollution, but also an impact of pollution on equilibrium capital growth. And even more worthy of mention, impact of pollution on green attitude affects equilibrium capital growth twofold. Capital growth can either slow down or accelerate. To analyze the change in capital growth, we use the saddle path dynamics illustrated in Fig. 8. We show that capital growth could either decrease or increase due to the impact of pollution on green attitude, if individuals chose the consumption ratio

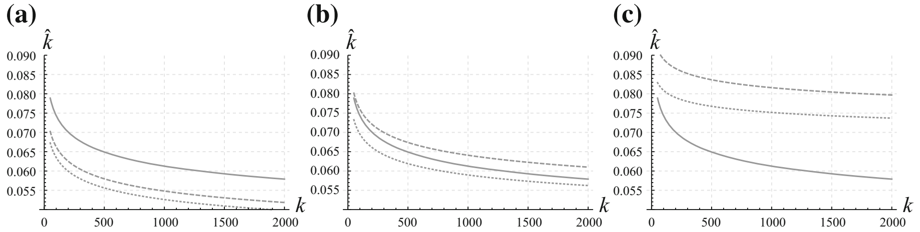

Fig. 10 Capital growth on the $\widehat{c/k} = 0$ locus; *solid line*: $\delta = \delta(k)$, *dashed lines*: $\delta = \delta(k, P)$ with low pollution $P = 3$, *dotted lines*: $\delta = \delta(k, P)$ with high pollution $P = 5$; parameters: $\varepsilon = 0.1$, $\rho = 0.05$, $A = 0.4$, $\gamma = 0.8$, $\xi_k = -0.1$. **a** Small impact of pollution: $\xi_P = -0.1$. **b** Moderate impact of pollution: $\xi_P = -0.17$. **c** Large impact of pollution: $\xi_P = -0.5$

associated with $\widehat{c/k} = 0$. Then we argue that the consumption ratio on the saddle path is lower than on the $\widehat{c/k} = 0$ locus. Hence capital growth will be faster on the saddle path.

Capital growth resulting from the consumption ratio μ_c and associated with the $\widehat{c/k} = 0$ locus can be calculated directly from (13). The change in capital growth due to increasing impact of pollution on green attitude is shown in Fig. 10. It depends mainly on the magnitude of this and on the level of pollution.

First, comparison of the dashed with the dotted curves shows that capital growth is linked negatively with the pollution level. As pollution enhances green attitude, individuals take more care about the environment. They increase abatement expenditure and decrease capital accumulation. This effect is the more pronounced the higher the pollution level. Hence, the resulting capital growth rate decreases with pollution.

Second, comparison of the dashed and dotted curves in the three diagrams shows that capital growth increases if the impact of pollution on green attitude becomes stronger (absolute value of ξ_P increases). Within the growth process, the pollution level decreases as shown above. In a setting where pollution enhances green attitude, a decreasing pollution level implies the opposite reaction. The improved environmental quality reduces individual responsibility for environmental issues, δ increases. Individuals take less care of environmental issues, abatement activity is reduced and capital accumulation accelerates. This effect is the more pronounced the stronger the impact of pollution on green attitude.

Since the saddle path is situated below the $\widehat{c/k} = 0$ locus, as demonstrate in Fig. 4a, individuals choose a consumption ratio smaller than μ_c. With a smaller consumption ratio, it follows immediately that capital growth is higher than displayed in Fig. 10. Consequently the overall effect on capital growth is ambiguous. The higher the pollution level, the more probable is a growth decreasing effect. The stronger the impact of pollution on green attitude, the more probable is a growth increasing effect.

The results about capital growth derived so far can also be used to understand what happens if an unexpected change in environmental quality applies. For example, with the Fukushima nuclear accident, pollution rose unexpectedly. As a reaction on the increased pollution level, green attitude enhanced. There was a broad acceptance of abatement strategies and the nuclear phase out was enacted. A decrease in capital growth caused by the change in energy policy would have been tolerated.

To conclude, the saddle path dynamics imply positive and decreasing capital growth in combination with a decreasing consumption ratio as shown in Fig. 4a together with 8. During this growth process, the pollution level decreases continuously due to capital accumulation since wealth influences green attitude positively (Fig. 9). A decreasing pollution level in turn weakens individual awareness of environmental quality. Hence capital growth is increased as given in Fig. 10. Consequently, the convergence process to the steady state with socially optimal levels of capital growth and pollution can either be accelerated by the additional impact of pollution on growth, if pollution is sufficiently high, or slowed down, if the impact of pollution on green attitude is sufficiently strong.

5 Conclusion

This paper focuses on the interdependency between green attitude, environmental quality and economic growth. We understand environmental externalities to be based on the incomplete perception of individual influence on environmental quality. Hence the determinants of this individual attitude towards the environment are centred, and we focus on the impact of wealth and of pollution on green attitude. Wealth enhances green attitude because increasing wealth enables environmental education and eases green consumption. Pollution has a positive impact on green attitude because with higher pollution the environmental consequences of economic decisions become more obvious. We show that economic growth as well as the level of environmental quality are crucially influenced by green attitude as well as by the evolution of green attitude.

Considering the impact of wealth on green attitude we show that both equilibrium growth rate and equilibrium environmental quality are subject to transitional dynamics. Capital growth is decreased due to the impact of wealth on green attitude. Within the growth process wealth increases, allows for more environmental education and improves green attitude. Hence, individuals are more aware of the consequences of their economic decisions on environmental quality and behave more environmentally friendly. Capital accumulation is decreased and pollution also decreases. Eventually, as a consequence of sufficiently high wealth, the individual's impact on environmental quality is completely included in the individual optimization calculus. Dynamic market equilibrium converges to the sustainable growth path.

The sensitivity of dynamics is highlighted by considering that environmental perception is not affected by individual wealth but is determined by environmental quality itself. For low pollution levels, individuals do not care about the impact of their activity on the environment. As environmental quality gets worse, we assume a higher sensitivity about the relationship between individual activity and aggregate pollution. However, given these assumptions, the aforementioned result of a transition to the sustainable growth path may not be retained. Instead, the resulting equilibrium is characterized by a constant level of environmental quality which still is suboptimally low. Due to the impact of pollution on green attitude, environmental quality is increased. Nevertheless equilibrium environmental quality remains constant and will not improve over time.

If both wealth and pollution jointly determine green attitude, the dynamics of capital growth and environmental quality influence mutually. The growing capital stock enhances green attitude and therefore leads to a decrease in the resulting pollution level. If pollution is high, green attitude is additionally improved, abatement activity increases and capital growth decreases. Nevertheless, improved environmental quality in turn weakens individual perception of environmental issues, hence convergence to the optimal growth path may be decelerated.

Appendix: Derivation of Transitional Dynamics

Transition to the long-run equilibrium is determined by the evolution of the consumption ratio, c/k, the pollution level, P, and the growth rate of capital, $\hat{k}$. Inserting (16) within (15) and solving for $\hat{P}$ yields

$$\hat{P} = \frac{1}{1 - \frac{\delta}{1-\delta}\xi_P}\left(\frac{\delta}{1-\delta}\xi_k\hat{k} - \widehat{c/k}\right) \tag{27}$$

One can see that the attitude towards the environment will centrally influence the development of pollution.

The dynamics can be determined from the growth rate of capital, $\hat{k}$, given in (13) and that of the consumption ratio, $\widehat{c/k} = \hat{c} - \hat{k}$. It is straightforward that the growth rate of capital is determined predominantly by the consumption ratio, c/k

$$\hat{k} \gtrless 0 \quad \Longleftrightarrow \quad \frac{c}{k} \lessgtr \frac{A}{1+\gamma(1-\delta)} \equiv \mu_k \tag{28}$$

with

$$\begin{aligned} \frac{\partial \mu_k}{\partial k} &= \frac{\gamma\delta_k A}{(1+\gamma(1-\delta))^2} \leq 0 \quad \Longleftrightarrow \quad \delta_k \leq 0 \\ \frac{\partial^2 \mu_k}{\partial k^2} &= \frac{\gamma A}{(1+\gamma(1-\delta))^3}(\delta_{kk}(1+\gamma(1-\delta)) + 2\gamma\delta_k^2) > 0 \quad \forall \quad \delta_{kk} > 0 \end{aligned} \tag{29}$$

Hence, if wealth exerts influence on environmental awareness, with $\delta_k < 0$ and $\delta_{kk} > 0$ by assumption, μ_k is a decreasing and convex function in k. If instead green attitude depends only on pollution, $\delta_k = 0$ and μ_k is independent from k.

The growth rate of the consumption ratio, $\widehat{c/k}$, can be calculated from the growth rate of consumption (14) and capital accumulation (13). Using $\hat{P}$ from (27) and the consumption growth rate (14) in $\widehat{c/k}$ results in

$$\widehat{c/k} = \varepsilon\left(A - \gamma(1-\delta)\frac{c}{k} - \rho - \gamma\left(1 - \frac{1}{\varepsilon}\right)\left(\xi_k\frac{\delta}{1-\delta}\hat{k} - \widehat{c/k}\right)\right) - \hat{k} \tag{30}$$

Inserting (13) and solving for the growth rate of the consumption ratio yields

$$\begin{aligned} \underbrace{\left(1 + \frac{(1-\varepsilon)\gamma(1-\delta)}{1-\delta-\delta\xi_P}\right)}_{>0}\widehat{c/k} &= -\left(\varepsilon\rho + (1-\varepsilon)\left(1 - \frac{\gamma\delta\xi_k}{1-\delta-\delta\xi_P}\right)A\right) \\ &\quad + \left(1 + \gamma(1-\varepsilon)\left(1 - \delta - \frac{\delta\xi_k(1+\gamma(1-\delta))}{1-\delta-\delta\xi_P)}\right)\right)\frac{c}{k} \end{aligned} \tag{31}$$

which leads to the evolution of the consumption ratio as given by

$$\widehat{c/k} \gtrless 0 \quad \Longleftrightarrow \quad \frac{c}{k} \gtrless \frac{\varepsilon\rho + (1-\varepsilon)\left(1 - \frac{\gamma\delta\xi_k}{1-\delta-\delta\xi_P}\right)A}{1 + \gamma(1-\varepsilon)\left(1 - \delta - \frac{\delta\xi_k(1+\gamma(1-\delta))}{1-\delta-\delta\xi_P)}\right)} \equiv \mu_c \tag{32}$$

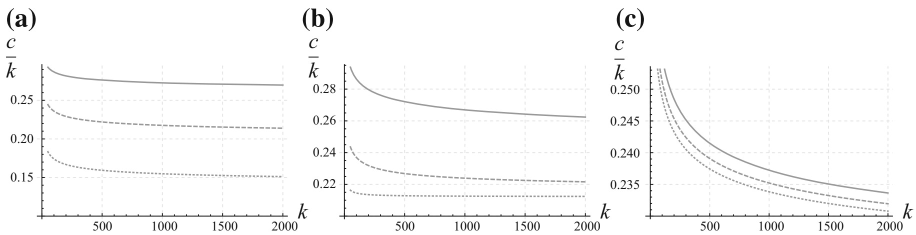

Fig. 11 $\widehat{c/k} = 0$ locus; parameters: $\varepsilon = 0.1$, $\rho = 0.05$, $A = 0.4$. **a** Environmental preferences; *solid line*: $\gamma = 0.5$, *dashed line*: $\gamma = 1$; *dotted line*: $\gamma = 2$; $\xi_k = 0.2, \xi_P = 0.2$. **b** Impact of wealth; *solid line*: $\xi_k = -0.1$, *dashed line*: $\xi_k = -0.3$; *dotted line*: $\xi_k = -0.8$; $\gamma = 0.8, \xi_P = 0.2$. **c** Impact of pollution; *solid line*: $\xi_P = -0.1$, *dashed line*: $\xi_P = -0.5$; *dotted line*: $\xi_P = -0.8$; $\gamma = 0.8, \xi_k = 0.2$

The numerator of μ_c decreases in k if and only if wealth is a determinant of environmental awareness, δ

$$\frac{\partial\left(\varepsilon\rho + (1-\varepsilon)\left(1 - \frac{\gamma\delta\xi_k}{1-\delta-\delta\xi_P}\right)A\right)}{\partial k} = -\frac{(1-\varepsilon)A\gamma\delta_k\xi_k}{(1-\delta-\delta\xi_P)} \leq 0 \iff \delta_k, \xi_k \leq 0 \tag{33}$$

Hence, if green attitude depends only on pollution, μ_c is independent from k, too. Nevertheless, if wealth has an impact on environmental awareness, the slope of μ_c with respect to k cannot be evaluated unambiguously, because the derivative of the denominator is ambiguous. However Fig. 11 shows that for all usual parameter settings μ_c is a convex and falling function of k whenever $\delta_k < 0$.

Unequivocally the $\hat{k} = 0$ locus will be situated above the $\widehat{c/k} = 0$ locus whenever positive growth is feasible

$$\begin{aligned}
\mu_k > \mu_c \iff & \frac{A}{1+\gamma(1-\delta)} > \frac{\varepsilon\rho + (1-\varepsilon)\left(1 - \frac{\gamma\delta\xi_k}{1-\delta-\delta\xi_P}\right)A}{1+\gamma(1-\varepsilon)\left(1-\delta-\frac{\delta\xi_k(1+\gamma(1-\delta))}{1-\delta-\delta\xi_P)}\right)} \\
\iff & A\left(1+\gamma(1-\varepsilon)\left(1-\delta-\frac{\delta\xi_k(1+\gamma(1-\delta))}{1-\delta-\delta\xi_P)}\right)\right) \\
& > \varepsilon\rho(1+\gamma(1-\delta)) + A(1+\gamma(1-\delta))\left((1-\varepsilon)\left(1-\frac{\gamma\delta\xi_k}{1-\delta-\delta\xi_P}\right)\right) \\
\iff & A > \rho(1+\gamma(1-\delta)) \iff \hat{k}(\bar{\delta}) > 0
\end{aligned} \tag{34}$$

To sum up, μ_k and μ_c are convex functions in k if there is an impact of capital on green attitude. They are both flat lines, if only pollution has an impact on green attitude. Moreover, μ_k is larger than μ_c. The resulting phase diagrams are given in Fig. 4.

Finally, for infinitely large capital, the $\hat{k} = 0$ locus as well as the $\widehat{c/k} = 0$ locus become flat lines as

$$\lim_{k\to\infty} \delta(k) = 0 \quad \Rightarrow \quad \lim_{k\to\infty} \mu_k = \frac{A}{1+\gamma} \equiv \mu_k^* \tag{35}$$

$$\lim_{k\to\infty} \delta(k) = 0 \quad \Rightarrow \quad \lim_{k\to\infty} \mu_c = \frac{\varepsilon\rho + (1-\varepsilon)A}{1+\gamma(1-\varepsilon)} \equiv \mu_c^* \tag{36}$$

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