How Discounting and Growth can be Good for the Environment

Sjak Smulders*
University of Calgary and Tilburg University

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Abstract

It is often argued that discounting future utility imposes a threat on the conservation of the environment for future generations. The same holds for productivity growth. Discounting puts a lower weight on the future and reduces optimal investment levels, both investment in productive man-made capital and in environmental assets. Productivity growth might bias investment towards investment in man-made capital, thereby crowding out environmental investment. We will show that implicit in these arguments are assumptions about whether the environment is mainly a source of productive inputs (i.e., a productive asset) or a (direct) source of utility. It is shown that, in contrast to conventional arguments, if society cares enough about the environment (thus acting as a durable consumption good), higher discount rates may increase optimal levels of environmental quality. If society cares relative less about environmental amenities, growth stimulates investment in environmental quality if the rate of intertemporal substitution is high.
This paper derives optimal investment rules in a neoclassical growth model with both man-made and environmental capital. We find that maximizing discounted utility may result in a level of environmental quality that *exceeds* the level that would be chosen when altruistically maximizing future generations' utility levels.

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* Department of Economics, SS438, University of Calgary, 2500 University Drive NW, Calgary, Ab, Canada T2N 1N4. e-mail: j.a.smulders@uvt.nl
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1. Introduction

Environmental problems arise from excessive pollution and depletion of natural resources. Since environmental change is often slow, the current generation may not be hurt much by these problems: the cost is shifted to future generations. High levels of pollution and rapid depletion are attractive to the current generation especially if they generate high levels of current output. Hence, a conflict may arise between high levels of output and growth on the one hand and low environmental quality for future generations on the other hand.

The higher a society's discount rate, the less current generations will take into account adverse effects on future generations. Many feel that the result is unfair. Instead, altruistic agents would like to endow future generations with highest possible sustainable levels of welfare. Lower discount rates should lead more easily to sustainable development, and often a low discount rate is imposed in analyses of optimal climate change policy (e.g. Stern 2006), which runs into problems of large gaps between optimal and actual savings rates and of calibration of historical savings and emissions (Nordhaus 2006). Human beings seem to act impatiently in practice, and altruistic feelings are easily dominated by the eagerness to take up the opportunities made possible by new technological developments.

When discounting and impatience are a fact of life, there is another mechanism that promotes sustainable development. In general, we care about the environment as an amenity. Our well-being not only depends on produced consumption goods but also on less materialistic needs. Just like we may give up some material welfare in exchange for more leisure or a life with more contact with friends and family, society may be willing to sacrifice some production for a clean environment. If the environment is a direct source of utility, even impatient societies may want to improve environmental quality provided that environmental improvements come at not too slow a rate.

This paper explores a simple model of economic growth and environmental change to study how society's discount rate and preference for a clean environment affect long-run environmental quality and living standards for future generations. First we determine what are the maximal sustainable levels of welfare for future generations. Following Phelps (1961) and Beltratti et al. (1995) we refer to this situation as the *Green Golden Rule* which is interpreted as the optimal strategy for an “infinitely altruistic society”. Then we determine optimal investment strategies of an “impatient society” that maximizes the discounted sum of future utility, including utility directly derived from environmental quality. Confronting the optimal investment strategies in the altruistic society and in the impatient society, it is found that even with "high" discount rates and/or "high" rates of technological progress, the discounting society may optimally invest more in environmental quality than the altruistic society. For this result we need that the environment is relatively important as a source of direct utility, rather than as a source of productive inputs. That is, the environment needs to be an important consumer durable.

Other environmental economists have pointed out that applying low discount rates not necessarily promotes sustainable development. E.g. Markandya and Pearce (1991) comment on the often proposed practice of choosing a lower discount rate to take into account future generations' environment when assessing investment projects. They argue that it is better to impose explicit sustainability conditions. As most other related work, their analysis is concerned with the micro-economics of environmental policy and no formal framework is used. We place this discussion in the context of a formal macro-economic growth model.

Musu (1994) and Beltratti et al. (1995) also use a formal growth framework. Using a different model, Musu (1994) finds some results that are similar to those in this paper. He did not however point out the economic intuition behind the results. This paper stresses the distinction between the environment as a productive asset and the environment as a consumer good to explain the results. Beltratti et al. (1995) find that the optimal level of environmental quality is always below its Green Golden Rule level. These authors restrict the analysis to a model with environmental investment only and no man-made capital, when comparing optimal investment and green golden rules. Rowthorn and Brown (1999) take the opposite approach by restricting their analysis to physical capital investment only and treating the environment as a flow variable. They focus on the effect of higher discount rates on optimal biodiversity conservation. It is found that an increase in the discount rate slows down physical capital investment and reduces the demand for land, either in the case that capital and land are close substitutes, or in the case that biodiversity is easily substitutable in utility. Lower intensity of land use enhances biodiversity. Krautkraemer (1988) studies the effect of discount rates on two types of assets: physical capital and a stock of non-renewable resources with amenity value. There is no growth in his model. Asheim (2005) studies the effect of discounting on long-run consumption levels in a general equilibrium model; his model has no growth in the long run, no abatement of pollution and no amenity value from environmental capital.

We extend the results of this literature by studying a more general model. We study the interaction between two types of investment: investment in the environment modeled as a renewable resource stock and investment in man-made capital. We allow for exogenous technological change driving growth in the steady state. We not only consider the effect of discounting on steady state environmental quality, but also investigate the effects of faster technological change and we study how much steady-state environmental quality differs from the levels that would maximize long-run utility levels.

2. The model

Our model combines a one-sector neoclassical growth model with exogenous technological progress and the standard renewable resource model. The renewable resource stock should be interpreted as an index for environmental quality. Renewable resource use (harvest) is equivalent to pollution in the model. By limiting pollution, the stock of resources renews itself and environmental quality improves. Pollution reduction thus implies investment in environmental quality. The other type of investment in the model is conventional capital accumulation. It is these two types of investments, investments in man-made assets and in natural assets, that determine the interaction between economic growth and the environment.

Production of final goods Y is given by a simple Cobb-Douglas specification:

$$(1) \qquad Y = (aN^{\chi})\,(T_L L)^{\alpha}\,K^{\beta}\,(T_P P)^{\omega} \qquad\qquad \alpha+\beta+\omega=1$$

where N is environmental quality, L is labour input, K is capital, P is natural resource use or pollution, T_L (T_P) is labour augmenting (resource-augmenting) technological progress, aN^{χ} is the total factor productivity term that depends positively on the quality of the environment, and α, β, and ω are the production elasticities of labour, capital and resources respectively (they are all positive).

We abstract from population growth, assume full employment, and normalize employment to unity (L=1). The two indexes of technology T_L and T_P evolve exogenously over time. A useful aggregate index of technology turns out to be defined by:

$$T \equiv (a\,T_L^{\alpha}\,T_P^{\omega})^{1/(1-\beta)}$$

We will assume that this technology index grows at a given rate g:

$$(4) \qquad \dot{T}/T = g.$$

The production function can then be rewritten as

$$(3) \qquad Y = N^{\chi}\,K^{\beta}\,T^{1-\beta}\,P^{\omega}$$

Produced capital goods comprise all kinds of reproducible productive assets like physical capital, knowledge (or human) capital, and infrastructure. Environmental quality N affects productivity, so that environmental quality acts as an input in production. This might happen because the health of workers is improved which boosts labour productivity, because soil quality improves agricultural productivity, or because wear and tear of buildings diminishes with improved air quality. The variable P captures inputs like mineral and energy use, and any other activity of the production process that implies extractive use of the environment. Hence, we can interchangeably label P as resource use, pollution and polluting inputs. for it.[1] Similarly, the variable N stands for both the stock of environmental resources and the quality of the environment. Environment quality evolves as a renewable resource:

$$(7) \qquad \dot{N} = E(N) - P, \qquad\qquad E_{NN}<0,\ E(0)=E(\overline{N})=0,$$

where $E(\cdot)$ has the usual inverted-U shape as depicted in the upper panel of Figure 1. The term $E(N)$ represents nature's capacity to renew itself and to assimilate pollution. We label it the absorption capacity of the environment. As long as the economy pollutes less that the environment can carry, i.e. $P<E(N)$, environmental quality improves over time. A non-deteriorating environment ($\dot{N}=0$) requires a constant pollution level P that does not exceed absorption capacity.

Man-made capital depreciates at rate δ. Output is used for consumption and investment in man-made capital, so that accumulation of man-made capital is given by:

$$(6) \qquad \dot{K} = Y - C - \delta K.$$

Household preferences are given by:

$$(11) \qquad W = \frac{\sigma}{\sigma-1}\int_0^{\infty}(C\cdot N^{\phi})^{\frac{\sigma-1}{\sigma}}\ e^{-\vartheta t}dt,$$

where $(C\cdot N^{\phi})^{1-1/\sigma}$ represents instantaneous utility, ϑ the utility discount rate ("impatience"), ϕ the preference for the environment ("greenness"), and σ the intertemporal elasticity of substitution ("flexibility").[2] Both produced consumption (C) and environmental amenities (measured by N) are arguments of utility.

Note that environmental quality contributes directly as well as indirectly to welfare in the model. It contributes directly because of amenity and existence values. It contributes indirectly because of its productive value (N enters the production function so that environmental quality boosts the production of consumption goods) and also because its ecological value (N affects nature's capability to absorb pollution so that

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[1] Pollution acts as an input in production since the more a firm is allowed to pollute, the higher its output can be. Reducing pollution at given levels of other inputs requires abatement measures (changes in the production process) which are generally costly and which reduce output. Hence, modeling pollution as an input implicitly models abatement activities.

[2] The specification implies an intratemporal elasticity of substitution equal to one, which is a necessary condition for balanced growth to be optimal, see Bovenberg and Smulders (1995).

environmental quality affects the availability of natural inputs to produce consumption goods).

3. Environmental quality and living standards on the balanced growth path

We first examine the relationship between long-run environmental quality and per capita income. In particular, we examine the characteristics of a balanced growth path on which output, capital and consumption grow at a constant rate, the savings rate is constant, and pollution equals absorption capacity so that environmental quality is constant.

Denoting by s the fraction of income saved, consumption equals $C=(1-s)Y$ and capital accumulation in (6) can be written as

$$(12) \qquad \dot{K} = sY - \delta K$$

Substituting (3) into (12), we solve for the growth rate of the capital stock:

$$(13) \qquad \dot{K}/K = s\, N^{\chi}\, P^{\omega}\, L^{\alpha}\, (T/K)^{1-\beta} - \delta$$

Since T grows at rate g, the growth rate of capital can be constant only if also K grows at this rate. Substituting g for the lhs of (13), we find that the capital technology ratio in the steady state is given by:

$$(14) \qquad (K/T)_{\infty} = [\, s\, P_{\infty}^{\omega}\, N_{\infty}^{\chi} / (g+\delta)\,]^{1/(1-\beta)}$$

where the subscrift ∞ is used to denoted long-run values.

In the long run, pollution is determined by absorption capacity so as to maintain environmental quality at a constant level:

$$(15) \qquad P_{\infty} = E(N_{\infty})$$

Substitution of (14) and (15) into the production function gives the following expression for per capita income:

$$(16) \qquad (Y/T)_{\infty} = [s/(g+\delta)]^{\beta/(1-\beta)}\, [E(N_{\infty})^{\omega}\, N_{\infty}^{\chi}]^{1/(1-\beta)}$$

This expression clearly indicates the long-run effects of a change in environmental quality on income. First, environmental quality directly affects income by boosting total factor productivity (N^{χ}). Second, it indirectly affects income by changing the capacity of the environment to assimilate pollution (E). The sign of this second effect depends on the initial level of environmental quality, since $E(N)$ is inverted-U-shaped. Define N_{msy} as environmental quality for which absorption capacity E is maximal. Starting from below (above) N_{msy}, increasing environmental quality boosts (hurts) long-run absorption capacity. On balance, income levels increase with environmental quality for low enough initial environmental quality, but decrease with it for high environmental quality levels since in the latter situation the total factor productivity gains are outweighed by declines in absorption capacity. Intuitively, a rich environment is more fragile and can only be maintained by giving up production. Figure 1 depict the relationships between environmental quality, absorption capacity and income.

insert Figure 1

Figure 1 The (green) golden rule

Y/T and E as function of N

Note that environmental quality does not affect the long-run growth rate of the economy, but only on production levels. Environmental policy affects growth in the short run, but in the long run capital cannot grow at a faster rate then exogenous technological change because of diminishing returns with respect to capital accumulation. Indeed, in the long-run, output, consumption, and capital grow at the same rate (g) as the technology index (T).[3]

4. Two investment rules: altruism vs impatience

This section derives two investment rules. Each of them specifies the fraction of income s that must be spend on capital accumulation and the level of environmental quality that must be aimed at in the long-run to satisfy a certain criterion. The first criterion is maximization of long-run utility levels $U(C,N)$, or equivalently the utility level of a generation living in the far future. We see this as an altruistic criterion. It extends Phelp's (1961) "golden rule" by taking into account the environment as a direct source of utility. The resulting investment rules are referred to as the Green Golden Rule.[4] Second, we derive the investment rules according to which intertemporal welfare is maximized, which we refer to as the impatience

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[3] This can be checked immediately from (16): since all variables on the right-hand side are constant, Y grows at the same rate as T. Since consumption C is a constant fraction $1-s$ of output, it grows at the same rate.

[4] Chichilnisky et al. (1995) introduced the term "green golden rule". Our discussion generalizes their work by allowing for substitution between polluting inputs and other inputs: Chichilnisky et al. assume $P=C$ and $Y=F(K,N)$.

criterion.

The Green Golden Rule

Momentanous utility is given by $C\cdot N^{\phi} = (1-s)Y\cdot N^{\phi}$. Eliminating Y using (16) and maximizing with respect to s and N, we find respectively:

$$(19) \quad s_{GGR} = \beta$$

$$(20) \quad -\frac{E_N N}{E}\omega = \chi + \phi(1-\beta) \qquad \text{Green Golden Rule}$$

We refer to (20) as the "*green* golden rule of environmental policy", defining the level N_{GGR}.[5] There is a positive and a normative implication. If the actual stock of environmental quality is below the green golden level, a more ambitious environmental policy raises long-run utility levels. If society wants to maximize long-run utility levels, it should set environmental policy according to the green golden rule.

To interpret the result, first note that the lhs of (20) is declining in N. The green golden rule implies $E_N<0$. That is, the altruistic society invest in environmental quality beyond the level for which sustainable yields are maximal ($N_{GGR}>N_{msy}$). If $\phi=0$, the green golden rule corresponds to maximizing output. As we have seen above, this requires a balance between the benefits from higher total factor productivity (parameterized by χ) and the costs of reducing sustainable pollution levels (as parameterized by ω). The more important environmental quality is as a direct source of utility (the higher ϕ), the more society is willing to give up production for environmental quality.

Second, consider the interaction between investment in man-made capital (as indicated by s) and investment in the environment as a consumption good (as parametrized by ϕ). According to the green golden rule, the more productive capital is, the more should be invested in it for future generations and the less should be invested in environmental quality to reach the best steady state for future generations (N_{GGR} falls and s rises with β provided that $\phi>0$). The amenity value of the environment is the reason for society to optimally invests in the environment beyond the level that maximizes economic output. Then not only output is below its maximum but also investment in man-made capital. The higher productivity of man-made capital is (as reflected in higher values of β), the more costly it is to reduce man-made capital investment in favour of investing in the environment as a consumption good (amenity). We will call this an "investment shifting effect" as investment

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[5] Chichilnisky et al. (1995) introduced the term "green golden rule". Our discussion generalizes their work by allowing for substitution between polluting inputs and other inputs: Chichilnisky et al. assume $P=C$ and $Y=F(K,N)$. The label "green" indicates the link to the "green accounting" literature that broadens the concept of income to reflect also components of welfare that are not produced.

is shifted from investment in the environment towards investment in man-made capital.

Optimal growth

We now consider the situation in which society maximizes intertemporal utility of the representative agent as given by (11), subject to (3) and (5)-(7). This maximization problem is only well-behaved if the integral in (11) is bounded. This requires that discounted momentanous utility approaches zero for $t \rightarrow \infty$. Since N is constant and C grows at rate g in the steady state, the discounted value of momentanous utility asymptotically grows at rate $(1-1/\sigma)g - \vartheta$. Hence, we need to make the following assumption:

(21) $\vartheta + g(1-\sigma)/\sigma > 0.$

The following Hamiltonian characterizes the maximization problem:

$$H^o = (1-1/\sigma)^{-1}(CN^{\phi})^{1-1/\sigma} + \mu\cdot[\, N^{\chi} L^{\alpha} K^{\beta} T^{1-\beta} P^{\omega} - \delta K - C \,] + v\cdot[\, E(N) - P \,]$$

where μ and v are the co-state variables (shadow prices) of the capital stock and environmental quality. The first order conditions are:

(22) $\partial H^o/\partial C = C^{-1/\sigma} N^{\phi(1-1/\sigma)} - \mu = 0$

(23) $\partial H^o/\partial P = \mu\omega Y/P - v = 0$

(24) $\partial H^o/\partial K = \mu\beta Y/K - \mu\delta = \mu\vartheta - \dot{\mu}$

(25) $\partial H^o/\partial N = \phi\, C^{1-1/\sigma} N^{\phi(1-1/\sigma)-1} + \mu\chi Y/N + vE_N = v\vartheta - \dot{v}$

Eliminating the shadow price μ by differentiating (22) with respect to time and substituting the result into (24), we find:[6]

(26) $\beta Y/K - \delta = \vartheta + (1/\sigma)\cdot[\, \dot{c}/c + (1-\sigma)\phi \dot{N}/N \,]$

This expression equates the net rate of return to capital (left-hand side of equation N6.26) to the required rate of return forgone utility (on the right-hand side) and is known as the

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[6] Differentiation with respect to time of the second equality in (22) gives: $\dot{\mu}/\mu = -(1/\sigma)\dot{c}/c + (1-1/\sigma)\dot{N}/N$. From the second equality in (24), we have $\dot{\mu}/\mu = \vartheta - \beta Y/K + \delta$. Elimination of $\dot{\mu}/\mu$ between these two equations gives (26).

"Keynes Ramsey rule".[7] In the long run, consumption grows at rate g and environmental quality is constant so that the Keynes Ramsey rule boils down to the "modified golden rule":

$$\text{(27)} \qquad \beta Y/K = \delta + \vartheta + g/\sigma$$

From this expression we can calculate the long-run optimal savings policy:[8]

$$\text{(28)} \qquad s^{*} \;=\; \beta \left(\frac{(g+\delta)}{\vartheta + g(1-\sigma)/\sigma \;+\; (g+\delta)} \right) .$$

Society optimally saves less in the steady state the more impatient it is (that is, the higher its ϑ is) and the lower its rate of intertemporal substitution (σ) is. It invests more if the returns to capital (measured by β) are larger, but the investment rate always falls short of the golden rule savings rate β.

To determine optimal environmental policy, we eliminate the shadow prices v and μ by substituting (the time derivative of) (22)-(24) into (25) and find:[9]

$$\text{(29)} \qquad \beta Y/K \;-\; \delta \;=\; \frac{\omega\, \dot{\overline{Y/P}}}{\omega\, Y/P} \;+\; E_N \;+\; \left(\frac{\chi \;+\; \phi\, C/Y}{\omega} \right) \frac{P}{N}$$

This expression equates the net return to capital (LHS) to the return on investment in environmental quality (RHS). Investment in environmental capital yields a return to society for four reasons. First, preserving the environment ensures the availability of a sink for wastes and a source of resources in future. The faster the productivity of polluting and natural resource inputs in production grow, the more attractive it is to preserve the environment as reflected in the first term on the RHS (note that $\omega Y/P$ is the marginal return of P). Second, improving environmental quality may improve the absorption capacity of the environment, as is reflected in the second term. Third, the environment improves

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[7] Society requires a higher rate of return if it is more impatient and more eager to smooth consumption (that is, if ϑ is large and σ is small). The term in brackets represents the rate of decrease in marginal utility of consumption over time ($-\dot{U}_c/U_c$). The faster marginal utility of produced consumption goods falls, the lower is the value of an increase in production capacity in terms of utility. Households only keep investing if they are compensated for this loss by a higher rate of return in terms of output. Hence, the faster marginal utility of produced consumption goods falls, the higher the required rate of return on investment is.

[8] Note from (6) that $Y-C-\delta K=gK$ in the steady state, so that $s=1-C/Y=(g+\delta)/(Y/K)$.

[9] First, divide both sides of the second equality in (25) by ν. Second, use $\nu=\mu\omega Y/P$ and $\dot{\nu}/\nu=\dot{\mu}/\mu+(\omega \dot{\overline{Y/P}})/(\omega Y/P)$ from (23) to eliminate ν and $\dot{\nu}/\nu$ respectively. Next, use $\mu=C^{-1/\sigma}N^{\phi(1-1/\sigma)}$ from (22) to eliminate μ. Finally, use $\dot{\mu}/\mu=\vartheta-\beta Y/K+\delta$ from (24) to eliminate $\dot{\mu}/\mu$.

productivity of man-made assets with elasticity χ. Fourth, the environment has an amenity value that is more important the larger ϕ is.

In the long run, Y, C, and K grow at rate g, and pollution equals absorption capacity ($P=E$), which are both constant. Substituting these results, and eliminating the net rate of return to capital between (27) and (29), we find:[10]

$$(30) \quad \left(\vartheta + \frac{1-\sigma}{\sigma} g - E_N \right) \frac{N}{E} \omega = \chi + \phi(1-s^*) \qquad \text{Modified Green Golden Rule}$$

This condition determines the optimal long-run level of environmental quality for the impatient economy, to be denoted by N^*. Since the lhs of (30) monotonically increases in N and the rhs is a constant, N^* is uniquely determined. Existence, that is $N^*>0$, requires that the lhs is smaller than the rhs for $N=0$, or:

$$(40) \quad \vartheta < E_N(0) \left(\frac{\chi + \phi(1-s^*) + \omega}{\omega} \right) - \frac{1-\sigma}{\sigma} g$$

5. Implications

Now it can be discussed how the optimal policy for the impatient society compares to that of the perfectly altruistic society. In particular, we want to know whether the impatient economy ends up with output below its maximally sustainable level, and whether it may leave a larger stock of environmental quality to future generations than the perfectly altruistic society. These questions boil down to a comparison of the results of the two investment rules defined above. The questions are also related to whether optimal levels of environmental quality increase or decrease if the discount rate (ϑ) becomes larger or if technological change (g) becomes faster.

Pollution reduction incentives in the impatient society

The optimal level of environmental quality for the impatient society depends on all parameters of the model. While for some parameter combinations, environmental quality is optimally lower than its Green Golden Rule level, for other combinations, the reverse may be true. We compare (20) and (30) to examine this.

The expression in (30) has a useful interpretation in terms of marginal costs and benefits

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[10] First, note from (27) that the left-hand side of (29) equals $\vartheta+g/\sigma$. Second, note that the growth rate of $\omega Y/P$, that is the first term on the right-hand side of (29), equals g since ω is a parameter and P is constant in the steady state. Finally, note that $C/Y=1-s$.

of investment in the environment. The lhs represents the marginal costs of a change in pollution through changes in productive inputs of which the production elasticity is ω. Reducing pollution today implies lower output today which translates in an annualized loss through the effective discount rate $\vartheta+(1/\sigma-1)g$. The $-E_N$ term represents the fact that a small temporary reduction in pollution increases future environmental quality and absorption capacity, allowing for E_N more pollution permanently. Hence, if $E_N>0$, improvements in absorption capacity mitigate the costs of pollution reductions. The right-hand side represents the marginal benefits of a change in environmental quality. It reflects the productivity and amenity effect, indicated by χ and ϕ respectively. The last term ($-\phi s^*$) reflects the interaction with man-made capital accumulation. The higher the rate of investment in man-made capital s^* is, the more costly an increase in environmental quality is since it crowds out man-made capital investment more. Hence, the last term reflects the opportunity costs of investment in the environment.[11]

The existence condition in (40) implies that the marginal costs of environmental policy fall short of the marginal benefits if starting from the lowest possible level of environmental quality ($N=0$). The condition reveals that preserving environmental quality in the steady state requires a discount rate that is not too high in order to avoid “discounting away” the benefits of investments in a clean environment. It also reveals that the more quickly environmental quality improves (high E_N), the more environmental quality matters for total factor productivity (high χ) and for utility (high ϕ), and the less production relies on pollution (low ω), the more easily a high discount rate can be reconciled with environmental preservation.

Why impatience may create a bigger environmental bequest than altruism

Equation (20) has a similar cost-benefit interpretation as (30). Comparing (30) to (20), we see that the impatient economy faces higher marginal costs because of the discounting term ($\vartheta+(1/\sigma-1)g$). While the altruistic society only cares about long-run outcomes, the discounting society trades off long-run benefits against short run costs. This “investment aversion effect” tends to reduce environmental quality below the green golden rule level. However, the impatient economy also faces higher marginal benefits, because the opportunity costs of environmental quality are lower ($s^*<\beta$). This shifts the composition of investment towards environmental investment.

If the environment is not an argument in utility ($\phi=0$), the impatient economy always chooses a lower level of environmental quality in the long run than the altruistic society since its marginal costs are higher. Both capital and the environmental are productive assets in this setting. Impatience induces lower levels of investment in productive assets.

If society attaches a value to environmental amenities ($\phi>0$), the environment is no longer a pure productive asset, but also acts as a (durable) consumer good. This value makes

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[11] Note that if $\phi=0$, the marginal productivity of N and K are equalized so that no first-order effects of a change in the composition of investment occurs.

society to invest more in the environment if it becomes more impatient. This can be seen from the fact that $s^* < \beta$ so that the marginal benefits on the rhs of (30) exceed those reflected in (20).

In sum, we have two opposing forces. On the one hand the impatient society invest less than the altruistic one, but on the other hand it shifts its composition of investment more in favour of environmental amenities. The following proposition characterizes which force dominates on balance:

Proposition 1: The impatient society prefers a higher environmental quality level than the altruistic society ($N^* > N_{GGR}$) if and only if

$$\text{(41)} \qquad \phi\,\beta\,\frac{E(N_{GGR})}{N_{GGR}} \;>\; \omega\,(\vartheta + \delta + g/\sigma)$$

Proof: If (41) holds, the lhs of (30) falls short of the rhs for $N = N_{GGR}$. Then, (30) can only be satisfied with equality if $N > N_{GGR}$, since the lhs of (30) increases in N.

Corollary: Define $F \equiv \max_{\phi}\{\phi E(N_{GGR})/N_{GGR}\}$.
If $\vartheta < F\beta/\omega - \delta - g/\sigma$, then a value $\phi_{\mathrm{GGR}} > 0$ and $\varepsilon > 0$ exist such that $N^* = N_{GGR}$ for $\phi = \phi_{\mathrm{GGR}}$ and $N^* = N_{GGR}$ for $\phi_{GGR} < \phi < \phi_{GGR} + \varepsilon$. If $\vartheta > F\beta/\omega - \delta - g/\sigma$, then, $N^* < N_{GGR}$ for any $\phi > 0$.

Proof: From (7) and (20) we have $\partial(E/N)/\partial N < 0$ and $\partial N_{GGR}/\partial\phi > 0$, respectively. This implies that the lhs of (41) increases with ϕ for small ϕ and might decrease for large ϕ. Hence, if the rhs of (41) is smaller than the maximal value that the lhs can attain by varying ϕ, there exists a value of ϕ, say ϕ_{GGR} for which (41) holds with equality (so that by construction $N^* = N_{GGR}$) and for which the lhs of (41) is increasing in ϕ so that also for larger values of ϕ (41) holds (so that by construction $N^* > N_{GGR}$).

A high discount rate (ϑ) does not necessarily prevent optimal environmental quality to exceeds the Green Golden rule level provided that environmental quality is an important direct source of utility (ϕ high). Hence, amenity values may offset impatience. However, if the discount rate exceeds a critical value, environmental quality is always below the golden rule level. Interesting to note is that condition (41) requires improvements in environmental quality to occur quickly relative to the depreciation of man-made capital (high E/N and low δ). Shifting investment towards the environment then brings quick gains in amenities without hurting man-made capital stocks too much.

Condition (41) does not give a closed-form restriction on parameters since the absorption capacity function $E(N)$ is left unspecified and N_{GGR} is determined implicitly by (20). Figure 2 illustrates the proposition for the specification $E(N) = \xi(1 - N^{\eta})N$.

When higher discount rates boost environmental quality

The discount rate ϑ has an ambiguous effect on optimal environmental quality. An increase in the discount rate on the one hand reduces overall investment, which implies a fall in the optimal level of environmental quality, but on the other hand, it will shift investment from physical capital accumulation to environmental improvements by the investment shifting effect explained above. The following proposition characterizes the effects of higher discount rates:

Proposition 2: An increase in the discount rate boosts environmental quality ($\partial N^*/\partial \vartheta > 0$) if:

$$(42) \qquad \phi\, \beta\, \frac{E(N^*)}{N^*} > \omega \left(\frac{(\vartheta + \delta + g/\sigma)^2}{g+\delta} \right)$$

Proof: Straightforward differentiation of (28) and (30).

Condition (42) is very similar to (41), which is not surprising: if higher discount rates imply higher environmental quality, it becomes more likely that the discounting society chooses higher levels of environmental quality than the altruistic.

Normally, higher discounting implies lower environmental quality in the optimum steady state. The environment can be seen as a productive asset (yielding ecological and productive services). Impatient societies tend to invest less in productive assets. Only when environmental quality is an important source of direct utility (that is, if ϕ is large), the investment shifting effect may dominate the overall reduction in investment and optimal environmental quality increases if society starts discounting more. In this latter case, the environment acts like a consumption good rather than a capital good, and any shift that makes investment less attractive stimulates optimal environmental quality.

Is growth good for the environment?

Finally, let us examine the effect of a higher rate of growth on optimal environmental quality. A higher rate of technological progress g affects investment incentives by changing the effective discount rate $\vartheta + g(1-\sigma)/\sigma$, and it affects the composition of investment by affecting the rate of investment in man-made capital s^*. The latter channel represents the by now familiar investment shifting effect, while the former channel represent the investment aversion effect. Note that the effective discount rate rather than the pure discount rate ϑ determines the willingness to give up consumption. Faster productivity growth implies higher future income, which tends to increase consumption at the cost of investment. However, it also implies higher returns to investment which makes it attractive to substitute future consumption for current consumption. If the income effect dominates the intertemporal substitution effect, which occurs if $\sigma<1$, the willingness to invest falls with g, as revealed by an increase in the effective discount rate $\vartheta + g(1-\sigma)/\sigma$. The effect of higher growth on the investment rate s^* depends on the intertemporal substitution rate for similar reasons, with s* declining in g is intertemporal substitution is low. The following proposition characterize how investment incentive and investment shifting effects work out on environmental quality if the growth rate increases:

Proposition 3: An increase in the growth rate boosts environmental quality ($\partial N^*/\partial g > 0$) if:

$$(43) \qquad \phi\, \beta \, \frac{E(N^*)}{N^*} \left(\sigma \; - \; \frac{\delta}{\delta + \vartheta} \right) \; > \; \omega \left(\frac{(\vartheta \; + \; \delta \; + \; g/\sigma)^2}{g + \vartheta} \right) (\sigma - 1)$$

Proof: Straightforward differentiation of (28) and (30).

Corollary:
If $\vartheta < \delta(1-\sigma)/\sigma$, more growth hurts the environment, unless $\phi E/N$ is “large”.
If $\vartheta > \delta(1-\sigma)/\sigma > 0$, more growth hurts the environment;
If $\sigma > 1$, more growth hurts the environment, unless $\phi E/N$ is “small”.

Consider first the role of intertemporal preferences by setting $\phi=0$ for convenience, that is we consider the environment as a pure investment good. Then, the rate of growth affects optimal environmental quality through the investment aversion effect only. Higher growth leads to less investment if society prefers a relatively smooth consumption pattern ($\sigma<1$), and investment in the environment is hurt. Intuitively, society likes to use the windfall profits from faster technological improvements for consumption purposes rather than for investment in order to smooth consumption over time. Only if $\sigma>1$, society optimally invests more since it is flexible enough to postpone the benefits of technological advance to later dates. In this case, higher growth tends to be associated with higher environmental quality.

Now consider the role of the environmental as a consumption good by allowing for positive values of ϕ. If $\sigma<1$, a higher growth rate leads to lower investment incentives, which might however be offset by a investment shift if s^* decreases. If $\vartheta>\delta(1-\sigma)/\sigma$, the investment rate s^* increases, which increases the cost of environmental policy, so that N^* falls for sure. However, if $\vartheta<\delta(1-\sigma)/\sigma$, the investment rate falls, thus making investment in the environment less costly. If environmental amenities are important and arise quickly (i.e. if $\phi E/N$ is large), the investment shifting effect dominates the investment aversion effect and environmental quality is stimulated by higher productivity growth.

Finally we have the case of high intertemporal substitution and amenity values ($\sigma>1$, $\phi>0$). In response to faster technological change, investment incentives go up, thus stimulating environmental investment, but also investment rates go up, thus making environmental policy more costly. The first effect dominates if the second effect is relatively small, which happens for low $\phi E/N$.

Figure 3 illustrates the findings. It concentrates on the empirically most plausible case with $\sigma<1$. Growth is only good for the environment if the discount rate is low enough and the environment is an important amenity that improves quickly over time.

6. Conclusions

Discounting is not necessarily a threat to environmental preservation. In the stylized neoclassical model of optimal growth of this paper, higher discount rates reduce *total* investment, but may induce a shift in the composition of investment away from investment in man-made capital toward investment in the environment. This shift is more likely to dominate if the weight of environmental amenities in utility is large and if environmental quality adjusts quickly to reductions in pollution levels. Previous models typically considered only one type of investment and therefore overlooked shifts in the composition of investment (e.g. Rowthorn and Brown 1999, Beltratti et al. 1995).

Faster technological progress, which ultimately speeds up economic growth, is not necessarily a threat to environmental preservation, provided that society has a high rate of intertemporal substitution. In contrast, if intertemporal substitution is low, society optimally smoothes (full) consumption by balancing high future output from technological improvements with high current levels of consumption which comes at the cost of total investment effort. Only if at the same time society attaches a large weight to environmental amenities and the environment improves quickly, investment in the environment may increase despite the fall in total investment. In this case the environment acts more as a consumption good than as an investment good.

The main message of the paper is that the effects of discounting and economic growth on optimal environmental policy mainly depend on whether the environment is mainly an investment or a (durable) consumption good. Local air and water quality, for example, could perhaps be characterized as predominantly having a consumption good character: local residents' well-being is directly affected by these environmental quality indicators. In many cases, these resources can also improve quickly over time once appropriate measures are taken. The model predicts that discounting and economic growth may induce improvements in these indicators. In contrast, the climate system and other global environmental resources are more of an investment character: damage to them will affect man-made capital stocks and soil fertility in the long run. Moreover, the adjustment speed of these environmental resources is slow. Discounting and economic growth might be infavourable to solving the environmental problems associated with these resources.

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Appendix

A useful specification of the absorption capacity function proves to be:

(A.1) $E(N) = \xi\cdot(1-N^{\eta})\cdot N$

Marginal absorption capacity then reads:

(A.2) $E_N = \xi\cdot[\,1 - (1+\eta)\cdot N^{\eta}\,]$.

The implied elasticity is:

$$\text{(A.3)}\qquad \frac{E_N N}{E} = \frac{1 - (1+\eta)N^{\eta}}{1 - N^{\eta}}.$$

Setting the expression in (A.2) equal to zero and solving for N gives the level of environmental quality associated to the maximum sustainable yield, N_{msy}:

(A.4) $N_{msy} = (1+\eta)^{-1/\eta}$.

Substituting this expression in (A.1) gives the maximum sustainable yield:

(A.5) $P_{msy} = \xi\cdot\eta\cdot(1+\eta)^{-(1+\eta)/\eta}$.

The Golden Rule level of environmental quality follows from equating the elasticity in (A.3) to $-\chi/\omega$ which gives:

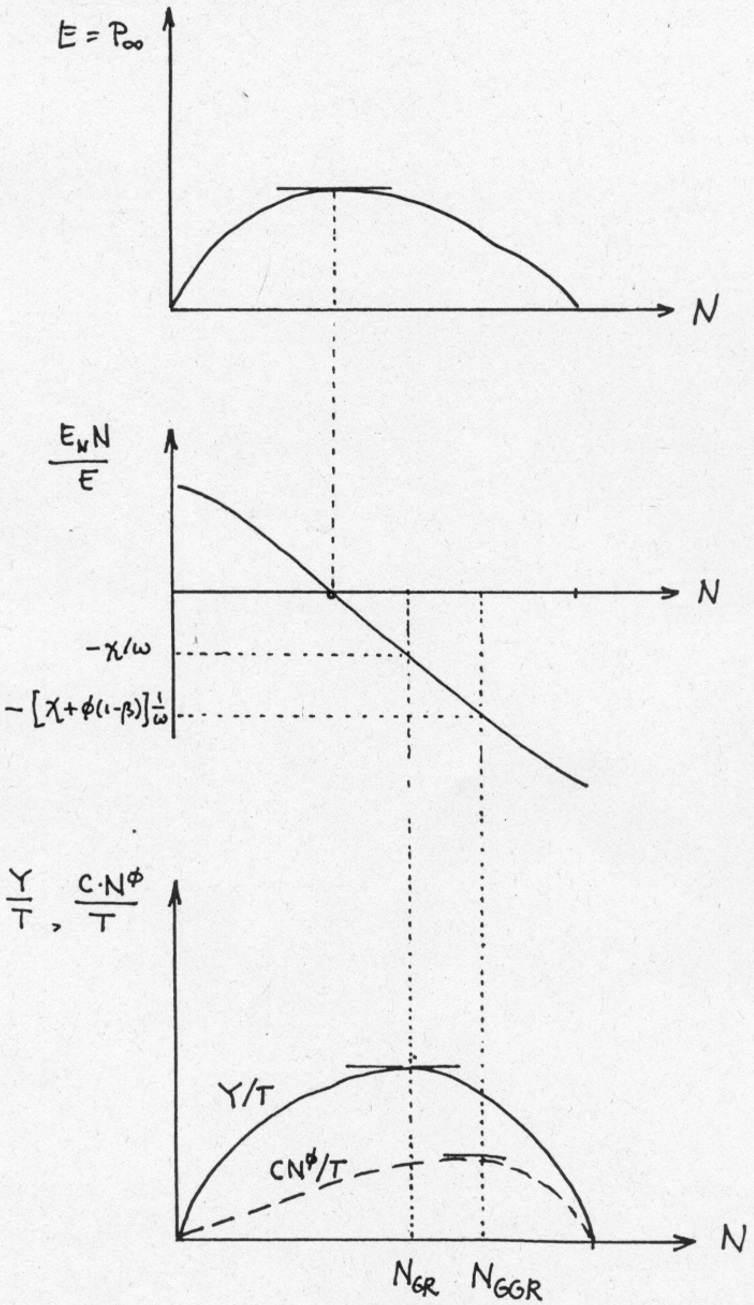
$$\text{(A.6)}\qquad N_{GR} = \left(1 + \frac{\eta\omega}{\omega+\chi}\right)^{-1/\eta}.$$

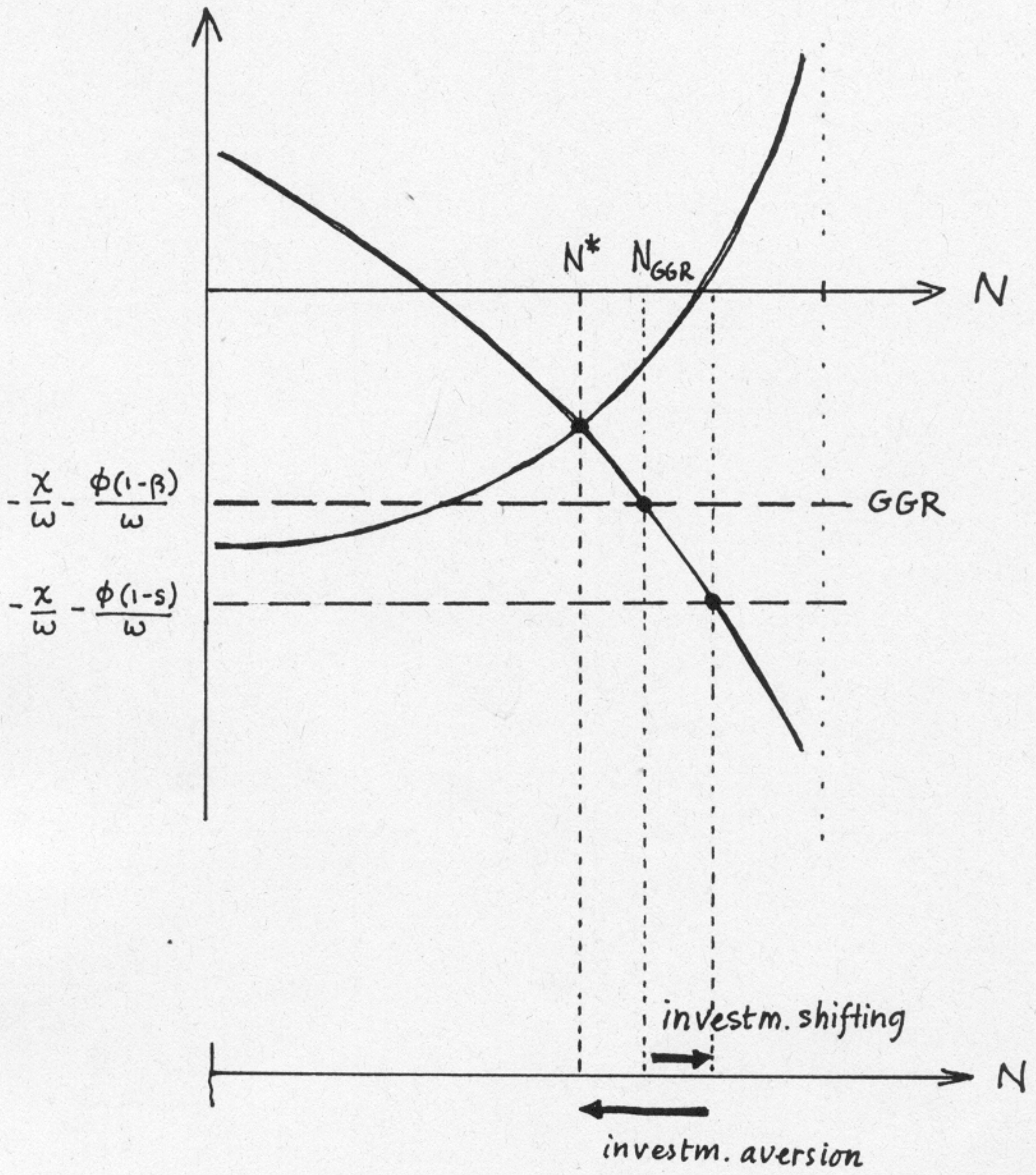
The Green Golden Rule level of environmental quality follows from equating the elasticity in (A.3) to $-\chi/\omega-(1-\beta)\phi/\omega$ which gives:

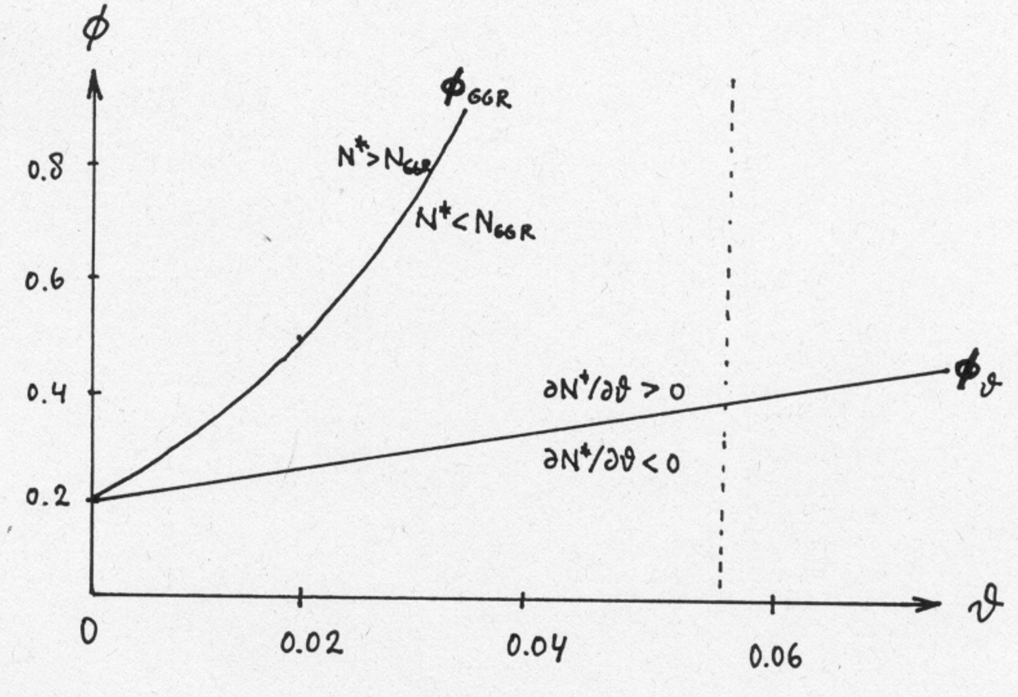
$$\text{(A.6)}\qquad N_{GGR} = \left(1 + \frac{\eta\omega}{\omega+\chi+\phi(1-\beta)}\right)^{-1/\eta}.$$

Finally, the optimal level of environmental quality follows from substituting (A.1)-(A.3) into (30) and solving for N which gives:

$$(\text{A.7}) \qquad N^{*} = \left(\frac{\left(1 + \frac{\chi + \phi(1-s)}{\omega}\right) - [\vartheta + (1/\sigma - 1)g]\frac{1}{\xi}}{\left(1 + \frac{\chi + \phi(1-s)}{\omega}\right) + \eta} \right)^{1/\eta} .$$


$E = P_\infty$
N
$\frac{E_N N}{E}$
N
$-\chi/\omega$
$-\left[\chi+\phi(1-\beta)\right]\frac{1}{\omega}$
$\frac{Y}{T}, \frac{C \cdot N^\phi}{T}$
Y/T
CN^ϕ/T
N
N_{GR}
N_{GGR}


N*
N_{GGR}
N
$-\frac{\chi}{\omega} - \frac{\phi(1-\beta)}{\omega}$
GGR
$-\frac{\chi}{\omega} - \frac{\phi(1-s)}{\omega}$
investm. shifting
N
investm. aversion


ϕ
0.8
0.6
0.4
0.2
0
0.02
0.04
0.06
ϑ
ϕ_{GGR}
$N^* > N_{GGR}$
$N^* < N_{GGR}$
ϕ_ϑ
$\partial N^*/\partial\vartheta > 0$
$\partial N^*/\partial\vartheta < 0$