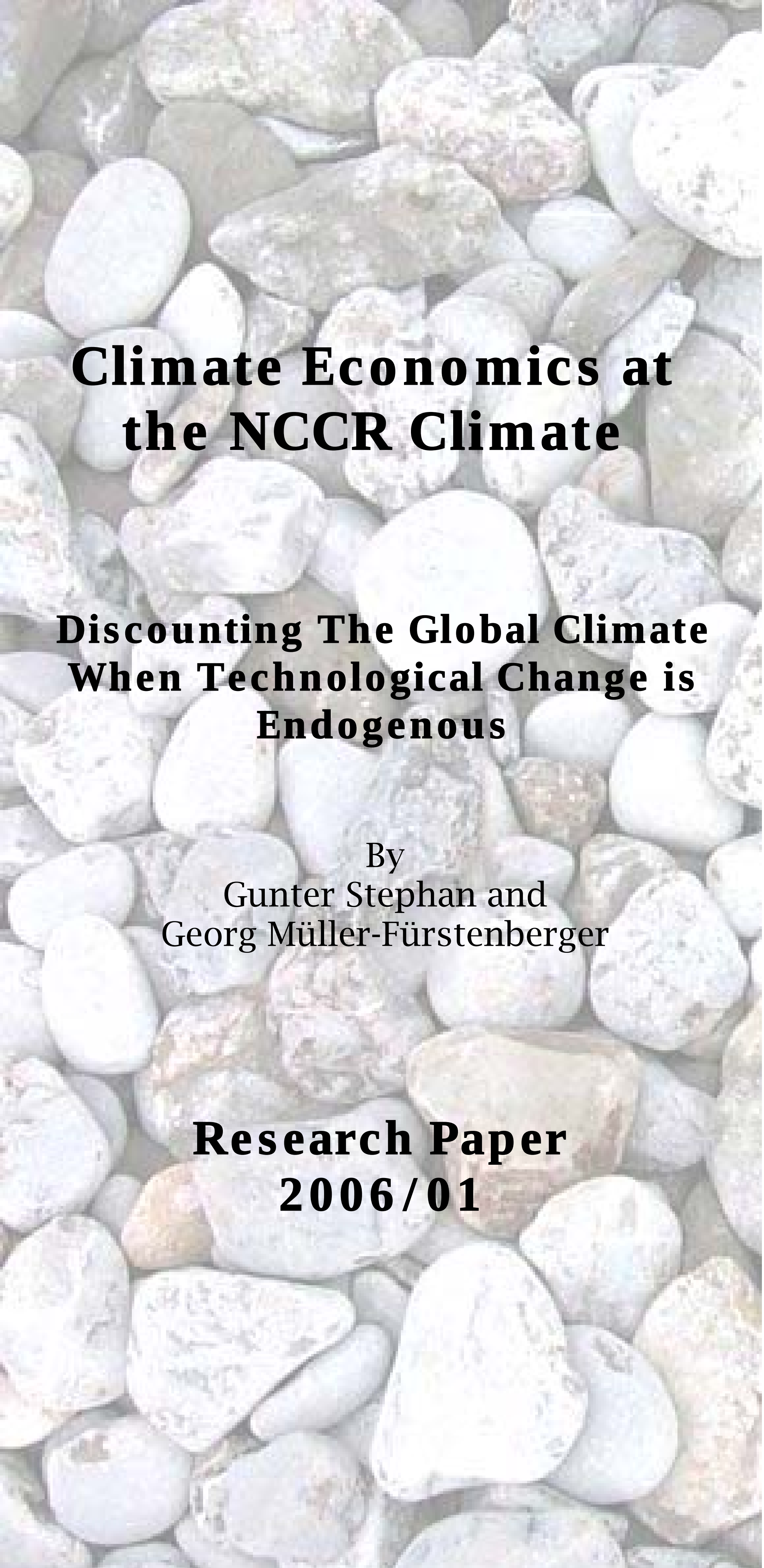

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## Discounting The Global Climate When Technological Change is Endogenous

By
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# Discounting The Global Climate When Technological Change Is Endogenous

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*Abstract:*

There are two polar views on the issue of discounting. One is to focus on intergenerational equity which means discounting utilities at low rates. Alternatively, the focus is on efficiency where the choice of the discount rate should imply rates of return that are similar to those that prevail in the capital markets. This paper analyses how different discount rates affect greenhouse gas abatement and endogenous technological change. Starting point is a simple analytical model where we show that higher discount rates cannot result in smaller stocks of atmospheric carbon. However, we cannot rule out the paradoxical result that a higher discount rate may lead to a higher knowledge stock. Therefore an Integrated Assessment Model is set up to take a closer look into the time pattern of emissions. Surprisingly, low discount rates lead to a sharp increase in emissions during the beginning of the time horizon, which, however, is overcompensated through higher efforts in greenhouse gas mitigation during the rest of the time horizon. Furthermore, at low discount rates, the potential to save energy through technological innovation is utilized faster and more pronounced than with higher discount rates.

*JEL Classification: Q40, O13.*

*Key-Words* : Integrated Assessment, discount rate, endogenous technological change, climate change.

# 1 Introduction

Two aspects are of central importance for the future of the global climate and - to a certain extent - for the future of the human society. These are the timing of greenhouse gas emissions on the one hand, and the de-carbonization of the economy on the other. The reason is quite obvious. Because of the tremendous inertia of the climate system, the earlier greenhouse gas emissions are abated, and the earlier less carbon intense or even carbon free technologies are innovated, the lower is the climatic impact of human activities, and hence the lower are the economics costs, future generations have to carry in responding to the challenge of global warming.

Welfare economics is based on the seemingly insipid presumption that preferences should count (see Pearce et al. (2003)). Since current emissions are small compared to the existing stock of atmospheric carbon, abatement costs are borne early, but benefits do not accrue until the distant future. Consequently, climate policy affects the welfare of the present and of the future generations, and discounting is a logical consequence from the basic value judgment of prescriptive economics.

However, discounting is not only a technical necessity. It also has an ethical dimension, for the higher is the discount rate, the lower is the weight placed on the welfare of future generations. Some find it ethically indefensible to treat generations differently, simply because they are born at different time. But not to discount implies discounting at rate zero and would lead - as is well known since Koopmans' pioneering work (see Koopmans (1965)) - to extensively high savings by the present generation. This is also difficult to defend, or as Arrow (1999, 16) writes: "… that all generations (should) be treated alike, itself reasonable, contradicts a very strong intuition that it is not morally acceptable to demand excessively high saving rates of any generation…".

In the past a lot has been published on the issue of evaluating costs and benefits of greenhouse gas mitigation, on the conflict between intergenerational equity and intertemporal efficiency, on the issue of discounting for the short-run versus for the long-term, as well as on the related problem of how best to discount the future in the case of uncertainty. For an overview, see Portney and Weyant (1999). This paper analyses an issue that is a bit aside of the main stream. Neglecting uncertainty it discusses the implications discounting utilities has when technological change is endogenous. More precisely, it analyses the question: How does the choice of a discount rate affect greenhouse gas abatement and the innovation of technologies?

Why is this an important issue to be considered? In principle there are two policy options for responding to the challenge of global warming. One is called a cap and trade policy, and the other is known as intensity targeting. The first one is in the spirit of the Kyoto Protocol and focuses on reducing greenhouse gas emissions. The second one corresponds to the policy the US has announced and argues for combating with the global warming through technical innovation.

Both, greenhouse gas mitigation and technological innovation can be viewed as investment into the future. Consequently, the choice of the discount rate affects both options. For example, Stephan and Müller-Fürstenberger (1998) have shown that there is an inverse relationship between the discount rate on the one hand and greenhouse gas abatement on the other. A rapid step up in near term abatement - even above efficiency levels – is observed, if a society places almost identical weight on the welfare of any generation.

Moreover, the choice of the discount rate affects the interaction between greenhouse gas abatement and technological innovation. For example, Goulder and Mathai (2000) observed a delay in greenhouse gas mitigation, if improvements in abatement technologies are expected. For, if abatement costs will be reduced by technological change, then it is profitable to abate more, but deferred into the future. Consequently, one might suppose that the way, discounting effects greenhouse gas abatement, is at least partly counterbalanced through technological innovation.

Summing up, this paper focuses on two questions: (1) How does the choice of the discount rate affect both greenhouse gas abatement and technological change? (2) How does the interaction between mitigation and innovation depend on the choice of the discount rate? Before proceeding to a numerical analysis at hand of an integrated assessment model (see Chapter 3), let us first clarify ideas in a simple model.

## 2 Some simple analytics

Global climate change is viewed as public bad and negatively affects conventional wealth. In each period $t = 0,\ldots,T$, the world's gross production net of climate damages can be consumed or might be invested into a stock[1] of energy-related technological knowledge. This is nothing else than to say that future is influenced through investing into knowledge capital and / or by investing into environmental capital through greenhouse gas mitigation.

To keep considerations as simple as possible, let carbon energy be the only input into production, and let production be characterized by a concave function $f(a(Z_t)e_t)$. $e_t$ represents the energy input which is measured in carbon equivalents to energy consumption, and thus directly governs the greenhouse gas emissions. $Z_t$ denotes the stock of technological knowledge and determines the energy efficiency $a(Z_t)$ of gross production (GDP). Note that with this formulation innovating new technologies can either increase the energy efficiency of production or reduce the carbon intensity of production.

Let the impact of global climate change be measured in terms of GDP losses only. These impacts are termed market damages in contrast to so-called non-market damages such as species losses, which are directly expressed in terms of welfare losses (see Manne and Stephan (2005)). Consequently, social welfare purely depends on the discounted sum of instantaneous utility U of consumption $c_t$. Let $\delta$ denote the discount factor, then any optimal allocation is a solution of

$$\mathrm{Max} \sum_{t=0}^{T} \delta^{-t} U(c_t)$$

subject to

$$e_t + \gamma Q_t = Q_{t+1}, \tag{2.1}$$

$$\theta(Q_t) f(a(Z_t)e_t) - (Z_{t+1} - \varepsilon Z_t) - c_t \geq 0. \tag{2.2}$$

Equation (2.1) describes the relationship between greenhouse gas emissions such as carbon dioxide ($CO_2$) and global climate change in the most simple way: The fu-

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[1] Here, technological change is driven by piling up a knowledge stock and innovation is viewed as a function of expenditure in research and development (see Nordhaus (2002)). However, this is not the only way to make technological progress endogenous. Alternatively, technological change might result from learning by doing (see Gerlach et al (2004)).

ture stock $Q_{t+1}$ of atmospheric greenhouse gases depends on the present concentration $Q_t$ as well as global emissions which directly corresponds to energy inputs $e_t$, while $\gamma$ denotes the factor by which natural abatement processes reduce existing stocks of atmospheric greenhouse gases.

Equation (2.2) describes the material balance of produced goods. $\theta$ is the economic survival factor and measures the fraction of conventional gross output that is at the society's disposal. That means, the more carbon energy is consumed over the time horizon considered, the higher is the stock $Q_t$ of accumulated global emissions, and hence, the lower will be the fraction $\theta(Q_t)f(a(Z_t)e_t)$ of conventional wealth that is available in period t.[2] This remaining fraction is called green GDP. Therefore equation (2.2) indicates, how green GDP is allocated between consumption $c_t$ and investment $(Z_{t+1} - \varepsilon Z_t)$ into the knowledge stock, where it is taken into account that without activity knowledge will erode at rate $1 - \varepsilon$.

Now suppose that there are increasing damages from carbon energy consumption, i.e., $\theta' < 0$, $\theta'' < 0$ and that production is characterized by decreasing returns of scale both in energy and knowledge, i.e., $f' > 0$, $f'' < 0$ and $a' > 0$, $a'' < 0$, respectively. Furthermore, let us assume that production is linear homogenous in energy and let us focus on interior solutions only. Then first order conditions imply the following Ramsey type conditions for optimality

$$(2.3) \qquad \theta(Q_t)a'(Z_t)f(e_t) + \varepsilon = \delta \frac{U'(c_{t-1})}{U'(c_t)},$$

$$(2.4) \qquad \frac{-\theta'(Q_t)a(Z_t)f(e_t)}{\theta(Q_{t-1})a(Z_{t-1})f'(e_{t-1})} + \gamma \frac{\theta(Q_t)a(Z_t)f'(e_t))}{\theta(Q_{t-1})a(Z_{t-1})f'(e_{t-1})} = \delta \frac{U'(c_{t-1})}{U'(c_t)}.$$

Putting together

$$\begin{aligned} &-\theta'(Q_t)a(Z_t)f(e_t) + \gamma[\theta(Q_t)a(Z_t)f'(e_t)] = \\ &[\theta(Q_t)a'(Z_t)f(e_t) + \varepsilon][\theta(Q_{t-1})a(Z_{t-1})f'(e_{t-1})] \end{aligned}$$

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[2] Alternatively, $1 - \theta$ measures the economic costs of global climate change in terms of foregone GDP.

allows for a nice interpretation. Since there are two option for investing into the future, either by investing into the knowledge stock $Z_t$, or by investing into climate quality through greenhouse gas mitigation, the above equation says that the opportunity costs of investing into knowledge through reducing abatement in period t-1 has to be equal of opportunity costs of extending abatement in period t.

What else can be concluded from our considerations so far? To achieve more insight, let us focus on what is called a stationary modified golden rule (see Burmeister and Turnovsky (1972)) by supposing that both stocks and flows stay constant over time, i.e., $c_t = c$, $e_t = e$, $Q_t = Q$, and $Z_t = Z$ for all t. Then from equations (2.3) and (2.4) immediately follows

$$\text{(2.3a)} \qquad \theta(Q)a'(Z)f(e) + \varepsilon = \delta$$

$$\text{(2.4a)} \qquad \frac{-\theta'(Q)a(Z)f(e) +}{\theta(Q)a(Z)f'(e)} + \gamma = \delta .$$

Now, let $\delta^* > \delta$ in the following, and let Q, Z, e, as well as $Q^*$, $Z^*$, $e^*$ denote the corresponding steady state values. Then from condition (2.4a) we can conclude that it is impossible that a higher discount rate can be associated with a lower stock of atmospheric carbon. To see this note that condition (2.4a) yields

$$\text{(2.5)} \qquad \frac{-\theta'(Q)f(e)}{\theta(Q)f'(e)} < \frac{-\theta'(Q^*)f(e^*)}{\theta(Q^*)f'(e^*)} .$$

Since $Q > Q^*$, we have $\theta(Q^*) > \theta(Q)$ as well as $e > e^*$, hence $f'(e^*) > f'(e)$. Therefore the denominator of the left hand side of inequality (2.5) is smaller than the one on the right hand side, hence

$$-\theta'(Q)f(e) < -\theta'(Q^*)f(e^*) .$$

Because of the assumptions made on $\theta$ this is in contradiction to $Q > Q^*$.

With a one-sector growth model a decrease of the discount rate always implies an increase of the optimal steady state capital stock. In the literature this phenomenon is called capital deepening (see Burmeister and Turnovsky (1972)). However, in models with heterogeneous capital such a response cannot be expected in general. For example, Burmeister and Dobell (1970) have shown that even in a well-behaved Cobb-Douglas world there is no unambiguous capital deepening. The possibility of substitution between different capital goods prohibits any hope that the stocks of different capital goods will – in any case - move into the same direction.

What does this mean for this analysis? We have shown that a higher discount rate cannot result in a smaller stock of atmospheric carbon, or to put it alternatively into a higher stock of environmental capital. Nonetheless, since environmental quality and knowledge are viewed as different capital goods, we cannot exclude that our models might exhibit a paradoxical behavior in the sense that a higher discount rate implies a higher knowledge stock. For if $Q^* \geq Q$, then $e^* > e$, and from equation (2.3a) follows

$$a'(Z)f(e) < \frac{\theta(Q^*)}{\theta(Q)} a'(Z^*)f(e^*) \leq a'(Z^*)f(e^*),$$

which is feasible even if $Z^* > Z$.

Steady state analysis typically reflects what happens over the very long run, but it bears no information about the traverse between different steady states or about adjustment to changes in the boundary conditions such as the discount rate. For getting more insight we will therefore concentrate in the following on a numerical analysis through employing a CGE based integrated assessment model.

## 3 Integrated assessment analysis

The following analysis is based on a top-down intertemporal general equilibrium model of integrated assessment. For details see Müller-Fürstenberger and Stephan (2006). For the present purposes it is reduced in complexity to be sufficiently transparent as to allow the implications of alternative viewpoints to be explored. It integrates sub models that provide a reduced-form description of technological innovation, the economy, emissions, concentrations, temperature change, and damage assessment.

## 3.1 Key features of the integrated assessment framework

As above, technological change will improve the energy efficiency, and hence, can allow for a higher gross output at lower energy inputs. Carbon dioxide ($CO_2$) is the only greenhouse gas, and the demands for carbon emissions are generated indirectly through a nested production function. That means, in each period t there are two input aggregates into gross production $y_t$. On the one hand these is carbon energy $e_t$, and there is value added $v_t$ on the other:

$$(3.1) \qquad y_t = \left[v_t^{\rho} + (a_t e_t)^{\rho}\right]^{1/\rho}.$$

There is Cobb-Douglas substitution between capital and labor, which together produce value added. And there is a less than unitary, but constant elasticity of substitution $\rho$ between the capital-labor aggregate $v_t$ and energy. Here we do not discern between conventional fossils similar to the types that are currently available and carbon-free energy that may be introduced in the future. Instead et is the aggregated input of different forms of carbon as well as alternative energy and is measured in carbon units.

Output productivity of energy is represented by $a_t$ which depends - as will be discussed below - on technological innovation. Thus, greenhouse gas abatement can result from reducing the amount of energy per unit of output, which may be achieved in two ways: either by substituting energy through labor and capital, and / or by increasing the energy efficiency of production. In both of these cases, abatement requires an economic investment.

Technological change is implemented by combining a capital vintage and Research and Development (R&D) approach. First, in each period there exists a stock $Z_t$ of technological knowledge, which can be enlarged through investment $m_t$

$$Z_{t+1} = \varepsilon Z_t + m_t^{0.5}. \tag{3.2}$$

As equation (3.2) indicates, R&D investments are characterized by decreasing returns, and technological knowledge devaluates at factor $\varepsilon$ over time. Note that decreasing returns reflect what is called a fishing-out effect and capacity constraints (limited pool of “brains”) in knowledge production (see Jones (1995)).

Second, technological improvements can affect energy productivity $a_t$ only, if new vintages of conventional capital are used in production. In other words, energy saving technological change is embodied and can be brought into application only, if a new vintage of physical capital is invested.

Now, let $n_t$ denote the fraction of new vintages of the total stock of physical capital that is available at the beginning of period t+1. Since new vintages support increases in energy efficiency, energy efficiency evolves according to

$$a_{t+1} = a_t(1 + \sigma_t n_t) \tag{3.3}$$

The efficiency improvement rate $\sigma_t$ is bounded between 0 and $\sigma^M$ and depends upon $Z_t$ according to

$$\sigma_t = (1 - e^{-Z_t})\sigma^M. \tag{3.4}$$

A "two-box" analysis is employed to cumulate carbon emissions over time, and to translate them into global concentrations. The numerical model is calibrated so that if there is zero abatement, concentrations will rise from 353 ppmv (the 1990 level) to 550 ppmv (twice the pre-industrial level) by about 2080. This leads to damages of 2.5% of gross output. At other concentration levels, the damages are projected as though they were proportional to the square of the increase in concentrations over the 1990 level (for details see Joos et al. (1999)).

For simplicity, we neglect the thermal inertia lag between global concentrations and climate change. We also neglect the cooling effects of aerosols and the heating effects of greenhouse gases other than carbon dioxide. Instead, potential global warming is directly attributed to increased atmospheric $CO_2$ concentration and will be translated into its economic impact according to a quadratic damage function $\theta_t$ which measures the fraction of conventional wealth that is available for disposal as green GDP.

Green GDP might be used for consumption, investment either into physical capital or technological knowledge and to cover energy costs. Labor is expressed in efficiency units, and it is inelastic in supply. Physical capital is accumulated just as in a conventional Ramsey model, and it is subject to intertemporal depreciation. Consequently, our calculations are based on the assumption that the world economy follows a Ramsey path, striking an optimal balance between consumption and investment into physical capital and knowledge. Solutions are obtained via Rutherford's sequential joint maximization method - a specialization of the Negishi approach (see Rutherford (1995)).

## 3.2 Results

As was mentioned in the introduction there are conflicting views on the issue of discounting. To test for the sensitivity of the results with respect to the utility discount rate, we take up these polar views and discern between two states of the word: (1) one in which intergenerational equity is an important issue, hence future utilities are discounted at low rates (1 % per year), and (2), one in which efficiency is the main focus, and hence the choice of the discount rate (3% per year) implies rates of return that are similar to those that actually prevail in international capital markets. This is said to be a descriptive scenario whereas in the first case the society has taken a prescriptive perspective.

Benchmark year is 2002, time steps are five years in length, and computations are carried out till the end of the century. Figure 3.1 presents the evolution of the global atmospheric carbon concentration both under a descriptive (3%) and prescriptive (1%) use of the discount rate. For judging these results it has to be kept in mind that our simulations are based upon two important assumptions. First, we focus on pareto-efficiency in greenhouse gas abatement, i.e., there is full cooperation among nations in global climate policy. Second, knowledge is global public good from which everybody can profit without any costs.

Putting together this explains why our simulations yield rather low atmospheric carbon concentrations. And since the optimal atmospheric carbon concentration is quite low, the differences between the two scenarios are also small, simply because the damages associated with such concentrations are very small. Nevertheless, it is obvious that with a lower discount rate the optimal stock of atmospheric carbon is smaller than with a higher discount rate.

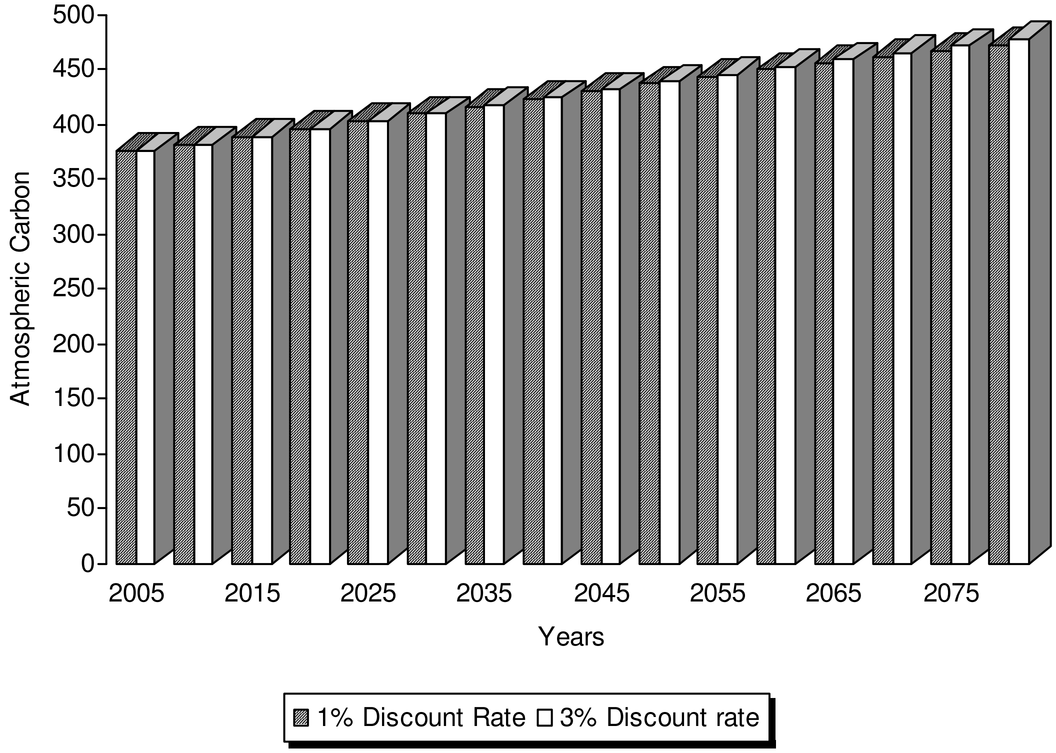

Figure 3.1: Atmospheric carbon concentration measured in parts per million volume (ppmv). The Benchmark level is 374 ppmv (2002-2003)

So far the results of the simulation are consistent to what we expect: The lower is the discount rate the more carbon dioxide emissions are abated, thus the more is invested into future environmental capital. However, a closer look into the time pattern of emissions exhibits a somewhat surprising outcome. As Figure 3.2 shows there is a significant difference in the time profile of $CO_2$ emissions under the states of the world. Compared to a descriptive approach with discounting utilities at a rate of 3%, a prescriptive perspective (1 % discount rate) would lead to a sharp increase in emissions during the first fifteen years which is, however, overcompensated through higher efforts in greenhouse gas mitigation during the rest of the time horizon.

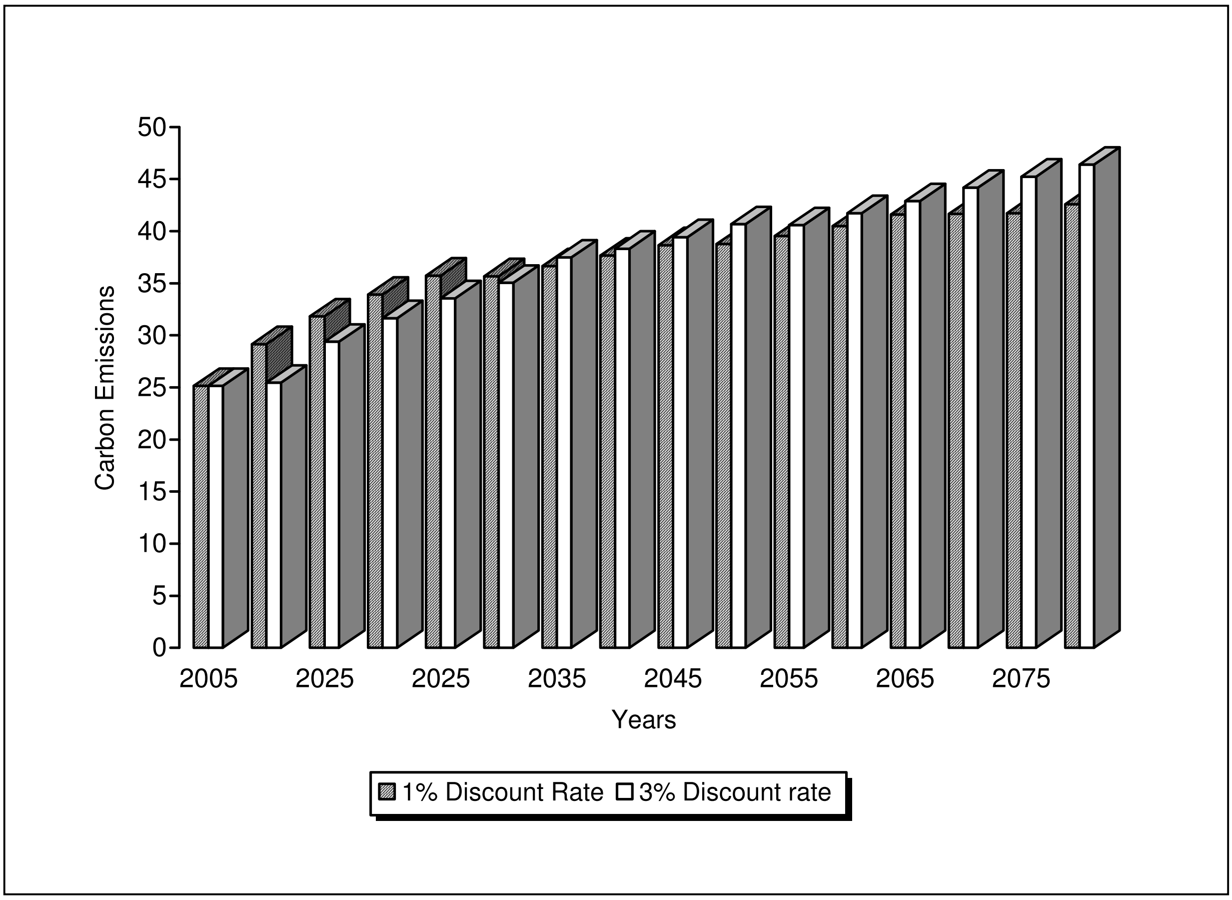

Figure 3.2: Carbon dioxide emissions (in giga tons)

In the literature this is called rebounding effect (see Geller and Attali (2005)). An explanation for that outcome is that in a prescriptive world the society puts a higher value on the welfare of future generations than in a descriptive one. Since future welfare depends on future consumption, thus on green GDP, a prescriptive society intends to invest as much as possible into the future capital stocks in order to grant high GDP and consumption potentials to the future generations. This in turn is possible only, if there is a significant step up in gross production, which means despite of technological innovations an increase of carbon energy consumption.

Within our integrated assessment framework, there are at least three options to check for that explanation. These are the development of per capital GDP as well as per capita consumption on the one hand, and these are the investments in physical as well as knowledge capital on the other.

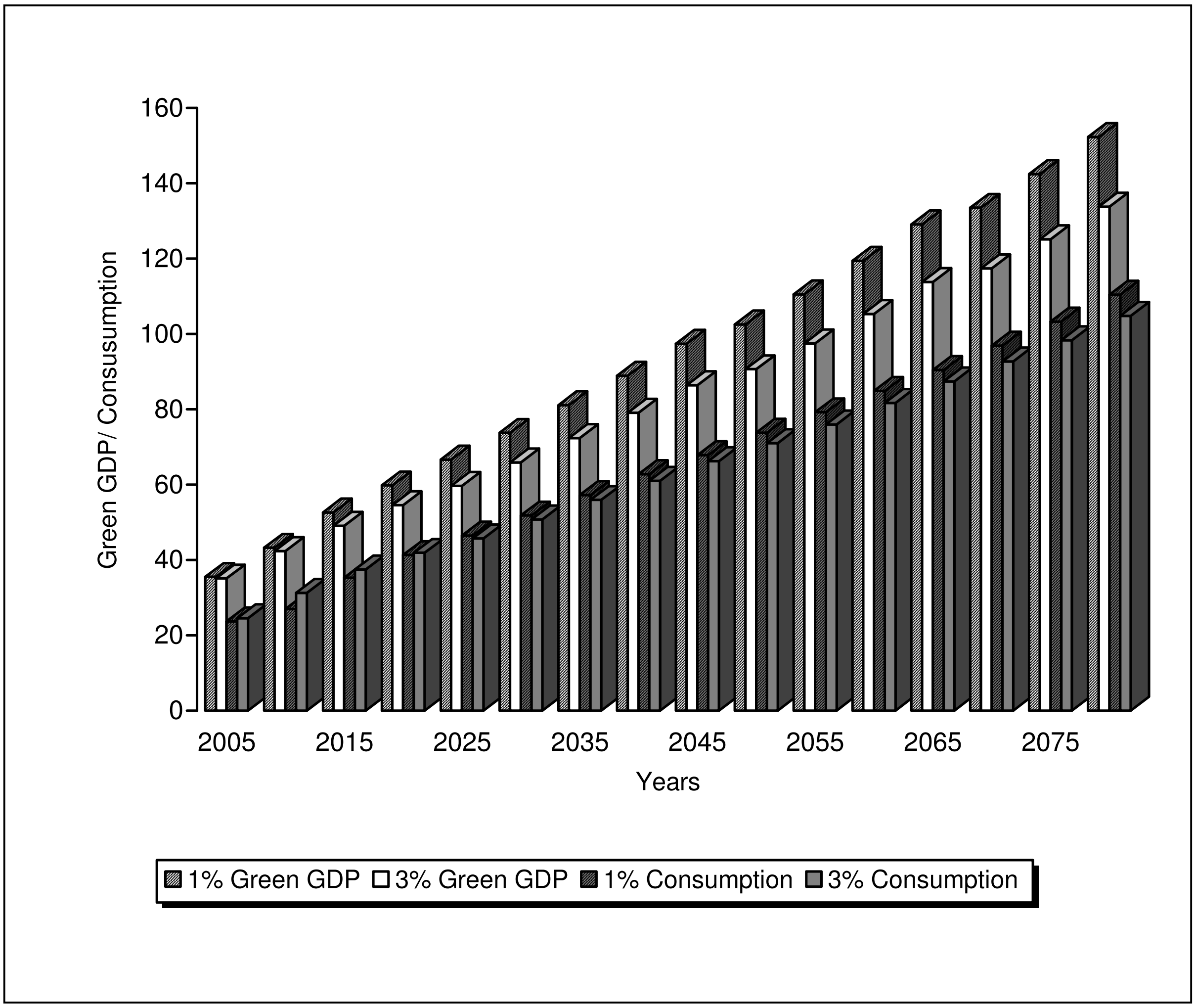

Figure 3.3: Green per capita GDP and per capita consumption

Figure 3.3 contains two kinds of information. First it displays, how global green per capital GDP changes over time, both for the 3 % as well as 1 % utility discounting scenario. Although differences seem quite small, the choice of the discount rate inversely correlates to economic growth, and leads roughly to a 30 % difference in green GDP in 2050.

Moreover, Figure 3.3 also shows that per capita consumption develops as we have anticipated. At the beginning of the time horizon per capita consumption in a prescriptive world is smaller than in the descriptive one, but grows faster. By the end of the time horizon in a prescriptive world per capita consumption is even higher than is a descriptive one.

This is a clear-cut indicator for what we have explained above. These differences in economic growth are due to the fact that the lower is the discount rate the more is invested into the future, either in terms of physical capital and /or technological knowledge and/or environmental capital. To see this, let us first consider the differences in the development of the stocks of physical capital.

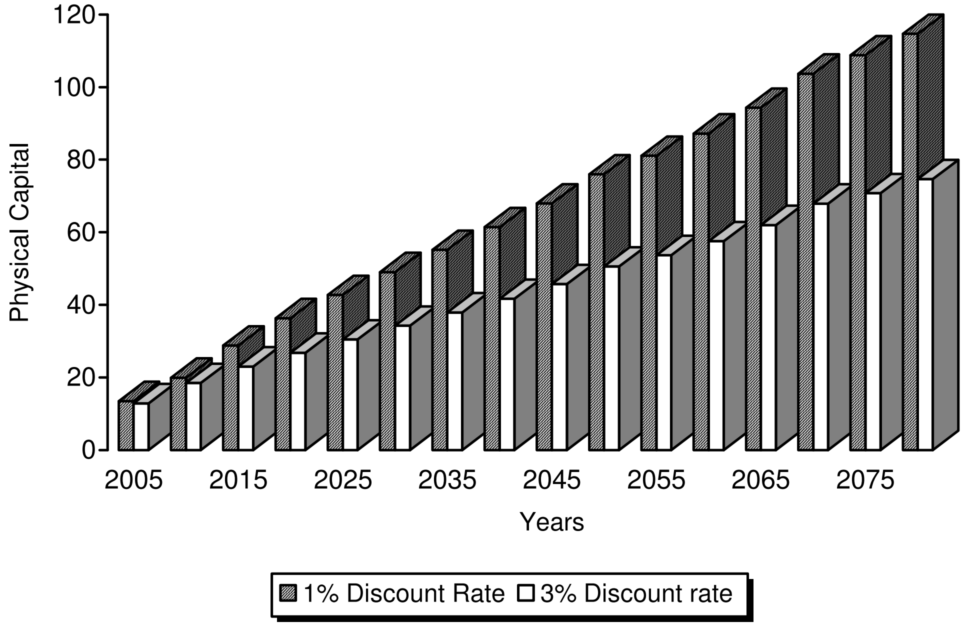

Figure 3.4: Physical capital stock (per capita values)

Figure 3.4 shows how the world's physical capital stock changes relative to the benchmark value (2002 world capital stock). Again significant differences are observed between a descriptive and prescriptive scenario, which become quite obvious after 2030. And the impact of the discount rate on physical capital investments is more pronounced than its impact on GDP. This is not surprising as the marginal rate of return declines for growing capital stocks.

Physical capital is only one of the three capital stocks we have modeled. The second one is a knowledge stock with respect to the application of energy in consumption/investment goods production. This intangible capital stock is directly related to the factor productivity of energy in macro-production (for details, see Müller-Fürstenberger and Stephan (2006)). The knowledge stock is augmented and maintained in the same way as physical capital; it takes stream of R&D expenditure to build it up and to keep it at a given level.

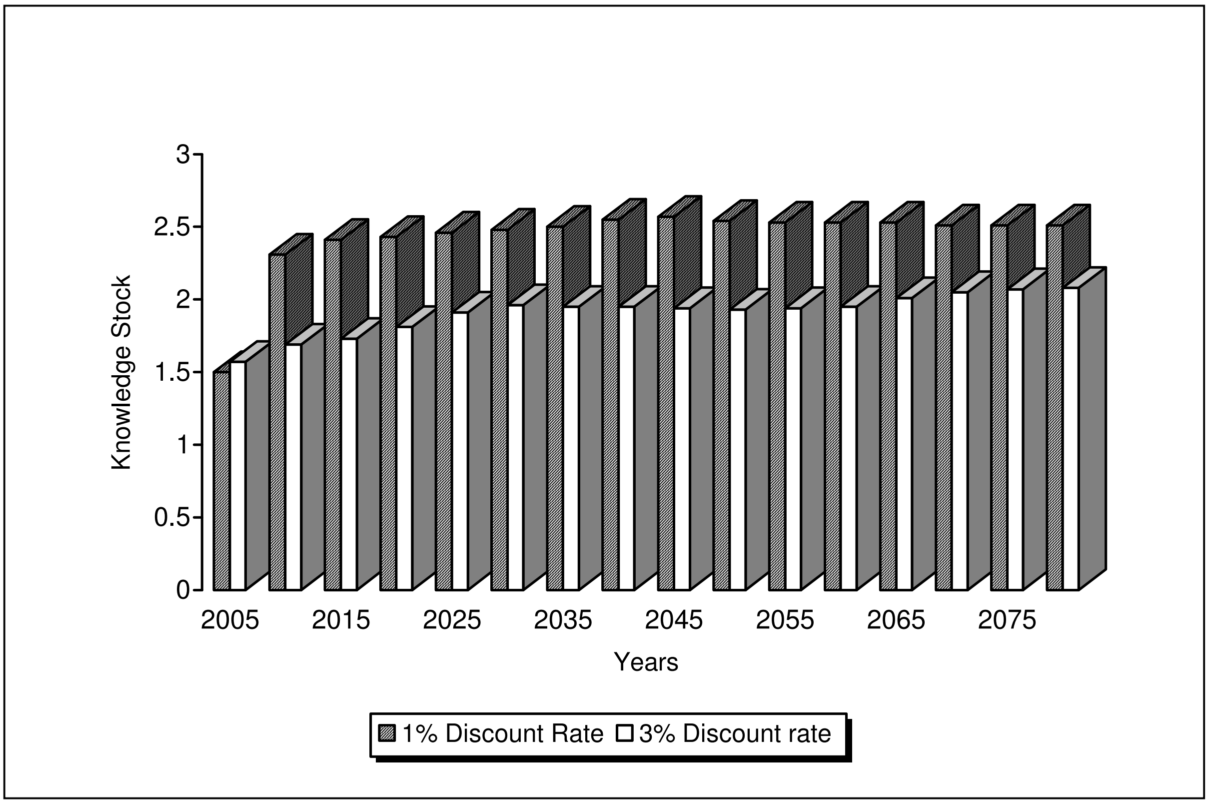

Figure 3.5: Knowledge stock relative to benchmark

Figures 3.5 exhibits the results for knowledge capital. If utilities are discounted at 3 %, the potential to increase efficiency of energy in macro production is rapidly increased and kept constant after 2010. By contrast, in the “prescriptive” scenario (1%

per year), the potential of R&D to save energy is utilized more pronounced and on a longer time-scale.

## 4 Conclusions

How does the choice of the discount rate affect greenhouse gas abatement as well as the formation of technological knowledge? By means of a simple analytical model we have shown that a higher discount rate cannot lead to a lower stock of atmospheric carbon. Here the so-called capital deepening phenomenon applies, but we cannot rule out that the knowledge stocks increase despite of an increase of the discount rate.

Although these results hold under quite mild assumptions, they apply only for the steady-state solution. Steady states give relevant information about the far distant future, which is of course of relevance in case of the global climate problem. However, to get some idea about the transitory behavior of the global economy – a phase, which is likely to take more than hundred years - we have extended our analytical considerations to an Integrated Assessment Analysis. The numerical simulation exhibited quite surprising patterns in the transitory phase. First, atmospheric carbon slightly goes up, when the discount rate is reduced from three to one percent. This is in contrast to our theoretical capital deepening result for the steady state. In the transitory phase the economy obviously experiences some type of rebounding effect. Second, knowledge accumulation is highly sensitive on the discount rate. The potential to improve the emission to GDP ratio is exploited very fast in the case of low discount rates.

What is the relevance of these findings and what are needs for future research? First note that there are different view on post-Kyoto policy options: One could be some kind of Kyoto-for-ever which means to set incentives for a pareto-efficient internationalisation of the external effects of global climate change through trading carbon emission rights on open global markets. Alternatively, one could vision providing greenhouse gas insurance through technological innovation - even without the need of international coordination and cooperation in greenhouse gas mitigation. Such a policy is advocated by the US administration and would require a fast exploitation of knowledge pools. Our analysis shows, that greenhouse gas intensity targeting might be in line with a cost-benefit analysis at low discount rates. However, for a more profound analysis future research should extend our framework in two directions. First, it should allow for non-cooperative behavior in the solution of the global climate problem. And second, it should take into account, which technological knowledge may result from learning-by-doing.

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