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Methodological and Ideological Options

Discounting, climate and sustainability

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ABSTRACT

Climate policy recommendations differ widely because of disagreements over what discount rates to use. Disagreement reduces the impact of economic models and signals a need for improved methodology. The problem is related to the choice of intergenerational welfare functions. A first questionnaire finds that the standard welfare function (SWF) fails to capture people's dislike of overshooting and fluctuating consumption paths. A second questionnaire reveals that when very-long-term sustainability of well-being is threatened, people's implicit discount rates resemble the low estimates used by the Stern Review. An alternative welfare function (AWF) reflecting consumption growth can potentially capture the preference structure revealed in both questionnaires. This makes the AWF an interesting candidate when searching for policies for sustainable development under uncertainty. Importantly, the questionnaires demonstrate that people are able to choose among policies by inspecting time graphs of policy consequences. Thus, it is possible to circumvent the complexities and disagreements introduced by welfare functions and discounting.

1. Introduction

According to Heal (1997) discounting has always been a source of controversy within the economics profession. Extensive advanced analyses of welfare economics have not resolved the underlying issues. Dasgupta (2008, p.167) remarks that "[i]ntergenerational welfare economics raises more questions than it is able to answer satisfactorily." This article, while focused on climate change and sustainability, takes a closer look at underlying assumptions that have not been properly tested until now.

It needs to be resolved whether the standard (social) welfare function (SWF) is representative of people's preferences regarding long-term developments. Of particular interest are preferences regarding overshoots in consumption (or well-being) in the form of fluctuations or unsustainable developments. If the SWF is not representative, are there better alternatives? One may even ask if it is possible to do without welfare functions and discounting. Could decision-makers simply rank order policies by inspecting graphs showing simulated policy consequences over time? In case welfare functions are used to search for or to rank policy proposals, what parameters do people's preferences for different time developments imply?

The practical problem of using the SWF is illustrated by the widely differing tax rates for greenhouse gases (GHGs) recommended by Nordhaus (2001) and the Stern Review (2007) (hereafter, "Nordhaus" and "Stern"). The fact that these tax rates differ by a factor of ten can predominantly be explained by the divergent arguments behind the authors' choices of discount rates (Nordhaus, 2007, p.700). Pronounced disagreements are present and problematic. While both studies do recommend positive GHG taxes, the wide gap between the recommended tax rates is likely to reduce policy makers' confidence in both the results and in the methods of analysis. Consistent with the academic debate, a recent report by the US Administration presents estimates of the social costs of carbon emissions that differ by a factor of five due to the same doubt about what discount rate to use (Interagency Working Group on Social Cost of Carbon, 2013).

The article is organized as follows. First, hypotheses regarding welfare functions are presented: the standard (SWF) and an alternative welfare function (AWF). Then comes the experimental design with two questionnaires and a discussion of the potential for overshoots and unsustainable developments in future per capita consumption or well-being. Third, results from the first questionnaire show that people dislike overshoots, an effect captured by the AWF but not by the SWF. The second questionnaire reveals very low implicit discount rates when subjects are confronted with unsustainable very-long-term developments. Fourth, the results are discussed in light of the academic debate over discounting. A distinction is made between the deterministic case and the case of uncertainty. The questionnaires demonstrate that people are able to choose between policies by inspecting their consequences in terms of time developments. Thus, one could avoid complexities and uncertainties introduced by welfare functions and

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discounting. The search for desirable policies can benefit from the use of the AWF, particularly in the case of uncertainty.

2. Hypotheses

How do people evaluate the welfare effects of various developments in per capita consumption? In particular, how do they react to overshoots in terms of fluctuations or unsustainable developments? One possibility is that they discount future utility according to a now standard (social) welfare function (SWF):

$$W = \sum_{t=0}^{\infty} u[c_t(P)]/(1+\delta)^t. \tag{1}$$

Here $u[c_t(P)]$ denotes utility derived from per capita consumption c_t in year t for policy P, and δ denotes the *utility* discount rate (also called the "pure rate of social time preference").[1] Single period utility is given as:

$$u[c_t(P)] = c_t^{1-\eta}/(1-\eta) \tag{2}$$

where η is the elasticity of the marginal utility of consumption, or *consumption elasticity* for short. For positive values of η, utility increases more and more slowly as per capita consumption increases (concave). When $\eta = 0$, utility equals consumption and δ will represent the more familiar *consumption* discount rate. The null hypothesis is:

H10. People make choices between per capita consumption developments according to the SWF. The SWF is followed consistently in that δ and η do not change with consumption scenarios.

A main reason to question this hypothesis is that the SWF does not discriminate against all types of non-monotonic consumption developments. Think of a consumption path that fluctuates around a monotonically increasing path. If both paths yield the same discounted utility, it seems likely that people would prefer the monotonic development. Hourcade et al. (2009) make the same point with illustrating examples.

One possible alternative welfare function (AWF) that is averse to fluctuations and overshoots is the discounted utility of relative *growth* in per capita consumption:

$$W = \sum_{t=0}^{\infty} u[g_t(P)]/(1+\delta)^t \tag{3}$$

where $g_t = (c_t - c_{t-1}) / c_{t-1}$ denotes the growth rate of per capita consumption in year t for policy P. As before, δ denotes the *utility* discount rate. The following single period exponential utility function is assumed:

$$u[g_t(P)] = \left(1 - e^{-g_t/\alpha}\right) \tag{4}$$

where the parameter α determines the concavity of the utility function. Since it seems that the AWF has not been used in intertemporal welfare economics before, it needs some further explanation and prior justification.

First, consider a situation where all allowable policies produce constant per capita consumption growth rates. Then there would be a fixed relationship between the constant growth rate and the consumption path that would follow. Hence, maximizing the sum of growth rates (AWF) would lead to the same result as maximizing the sum of per capita consumption (SWF) over time. Since both utility functions are increasing monotonically, this conclusion is not changed by the introduction of utility. Nor does the utility discount rate matter in this case.

Second, consider minor deviations from the constant growth rate scenario. Since consumption accumulates growth rates over time, consumption will react only gradually to deviations in growth rates. Intuitively, this suggests that the SWF must operate with lower utility discount rates than the AWF to yield similar conclusions. This intuition can be tested by the use of Nordhaus' DICE model.[2] The standard version of DICE makes use of the SWF with $\delta = 1.5\%$ p.a. and $\eta = 2$. When the SWF is replaced with the AWF with $\delta = 1.5\%$ p.a. and $\alpha = 0.02$, the savings rate ends up about 15% above the one for the SWF. With a higher discount rate for the AWF of $\delta = 2.5\%$ p.a. the two welfare functions give nearly identical results.

Third, the above test worked well because DICE produces positive consumption growth rates that do not change much over time. If the model had produced fluctuations or overshoots in consumption, the AWF would have led to different policy recommendations. While both welfare functions make use of concave utility functions, much larger relative variations in growth rates than in yearly consumption explain the difference.

The AWF is supported by several empirical findings. The Easterlin paradox says that the level of consumption does not matter for happiness, except when basic needs are not satisfied (Easterlin, 1974). While this may be true and should be taken into consideration, it is not obvious that it is fully reflected in people's preferences. Most people seem to prefer more to less. However, such preference may to some extent be cast in terms of preferences for growth. Frederick et al. (2002) refer to research showing that people prefer improving sequences of wages to declining sequences, present values being equal. Scitovsky (1976) argues that pleasure derived from change is more important for well-being than comfort. If change is stimulated by growth, while comfort relates to the stock of durable consumer goods, growth matters more than the level of consumption. According to prospect theory (Kahneman and Tversky, 1979) people consider projects in terms of losses and gains around reference points rather than in terms of effects on total wealth. Duesenberry's ratchet effect (Duesenberry, 1949) suggests that negative growth may have a stronger absolute effect on utility than positive growth (concave utility function).

A few more clarifying comments are needed. First, leaving out considerations of basic needs in the AWF is probably of limited concern in aggregate models with a minimum of growth potential. It seems far more important when considering distributions between groups. Second, exponential utility means that the AWF does not show diminishing sensitivity to negative growth rates, different from the treatment of losses in prospect theory. However, in aggregate *planning* models it does not seem desirable to play down the importance of large negative growth rates.

The null hypothesis reads:

H20. People make choices between per capita consumption developments according to the AWF. The AWF is used consistently in that δ and α do not change with consumption scenarios.

A second type of question concerns the *sizes* of implicit utility discount rates and consumption elasticities that can be derived from subjects' choices among scenarios for per capita consumption or well-being. How do the implicit parameters compare to the assumptions made by Nordhaus and Stern?

3. Experimental Design

The first questionnaire with questions Q1 and Q2 deals with overshooting and fluctuating consumption developments. The second, with questions Q3, Q4, and Q5, deals with very-long-term unsustainable developments where well-being never recovers after an overshoot.

[1] The welfare function represents a situation with a constant population or one where population size only influences per capita consumption.

[2] Version DICE-2007.delta.v8 (Nordhaus, 2008).

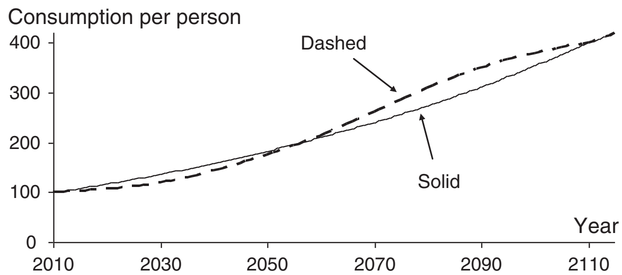

Fig. 1. Per capita consumption paths for Q1.

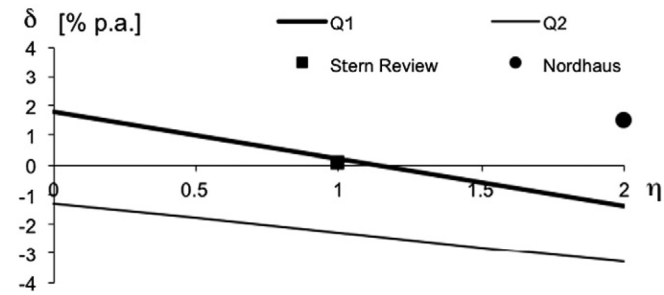

Fig. 3. Indifference curves based on the SWF for Q1 and Q2, and assumptions made by Nordhaus and Stern.

3.1. First Questionnaire

In questions Q1 and Q2, subjects were asked to choose one of two per capita consumption paths or declare indifference. Paths were said to be equal after 2110. Time horizons were chosen such that new-borns at the time of the questionnaire still could be alive at the end of the period. The Appendix A shows the exact wording.

Fig. 1 shows the two monotonically increasing consumption paths that subjects could choose between in Q1. Growth rates decline over time; the typical assumption in integrated assessment models. The solid curve represents a policy that benefits the near term to a larger extent than the dashed curve.

Fig. 2 shows the options in Q2, one monotonically and one non-monotonically increasing consumption path. The latter represents a mild form of unsustainable development as the solid path overshoots after having been the higher in the near-term. As will be shown below, if subjects choose the solid curve in Q1 and the dashed curve in Q2, this will be inconsistent with the use of the SWF.

The solid curve in Q2 differs from the simplifying assumption of steady growth in integrated assessment models. While simplification is always needed, both Nordhaus and Stern point to essential factors that have been left out of their models. Nordhaus and Boyer (1999) writes that: "Outside of the rarified and generally stylized models used in the climate-change integrated-assessment models, there are essentially no models of the world economy upon which to draw (p.8)." Dasgupta (2008, p.149) observes that: "…it has become a habit among economists to confine attention to forecasts in which consumption increases indefinitely." Accordingly, both Nordhaus and Stern build on (mostly) exogenous assumptions about economic growth and they study how climate change alters (mostly) predetermined consumption paths. Whether climate change leads to non-monotonic consumption paths in these studies is difficult to say because the publications do not show per capita consumption developments over time. Stern alludes to this possibility in the executive summary when saying: "… unabated climate change, which will eventually pose significant threats to growth." (p.xiii). Negative effects on GDP per capita in Stern's study range from zero to 35% in year 2200 (p.157).

Hourcade et al. (2009) call for "growth models that do not take the stability of growth pathways for granted" and that capture "transitory disequilibria". This calls for models that capture delays, feedbacks, and nonlinearities. When such complications are in place, series of laboratory experiments, all replicating field data, show that misperceptions can lead to non-monotonic developments, for instance: asset market bubbles (Smith et al., 1988), renewable resource depletion (Moxnes, 1998), instability of supply chains (Sterman, 1989), bankruptcy of businesses with new and popular products (Paich and Sterman, 1993), and fluctuations in commodity markets (Arango and Moxnes, 2012). The Great Depression of the 1930s and the financial crisis of 2008 illustrate a widespread inability to forecast and, more importantly, a failure to prevent non-monotonic global developments via the enactment of stabilizing policies.

The overshooting path in Q2 is probably less representative of effects of climate change than of for instance depletion of crude oil. If, at on-going prices, production from oil reservoirs starts to decline faster than alternatives to oil grow, oil prices will soar. The result could be non-monotonic development in consumption. Even if this should not be the most likely scenario, considerable uncertainty implies that overshoots may occur and should influence decisions under uncertainty. Furthermore, different underlying growth rates around the world means that the likelihood of periods with negative growth is higher for some groups than for others. For instance, the real median income for men in the US has been nearly stagnant since 1970 (Commerce, 2012).

To test if subjects behave according to the SWF (H_{10}), indifference curves for Q1 and Q2 are used as benchmarks, see Fig. 3. The indifference curves show combinations of parameters δ and η that give the same value of W (Eq. (1)) for the two consumption paths in each of the questions Q1 and Q2. On the x-axis is consumption elasticity η over a range covering assumptions made by Nordhaus and Stern. Indifference utility discount rates δ vary along the y-axis. Indifference *consumption* discount rates can be found where $\eta = 0$ (Eq. (2)) and are plus 1.78% p.a. for Q1 and minus 1.30% p.a. for Q2, respectively.

If subjects choose the solid path in Q1, the SWF predicts that they have δ-values above the upper indifference curve. If they choose the dashed path in Q2, the SWF predicts that they have δ-values below the lower indifference curve. So, if subjects make exactly these two choices, they cannot behave according to the SWF with one set of parameters. H_{10} can be rejected.

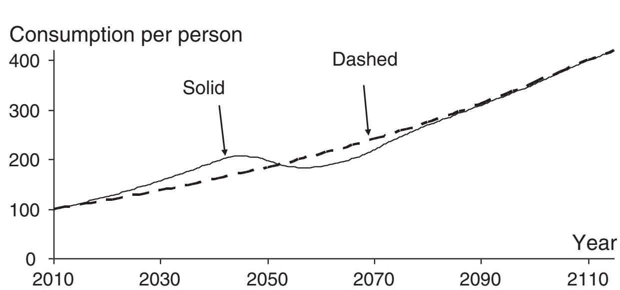

Fig. 2. Per capita consumption paths for Q2.

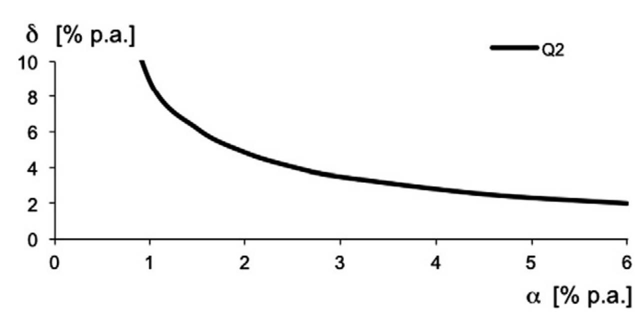

Fig. 4. Indifference curve for AWF for Q2.

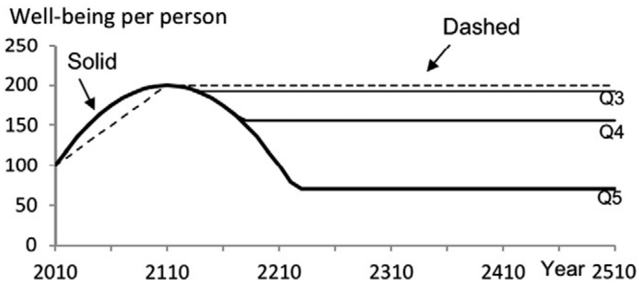

Fig. 5. Per capita well-being paths for Q3, Q4, and Q5.

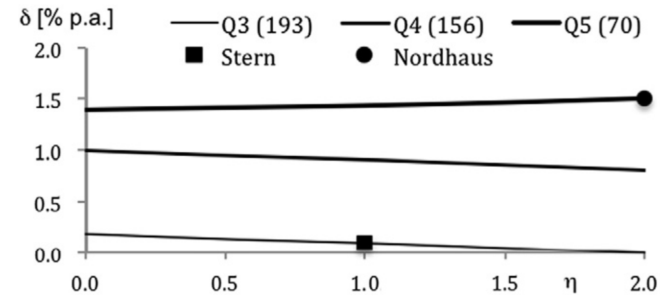

Fig. 6. Indifference curves based on the SWF for Q3, Q4, and Q5, and assumptions made by Nordhaus and Stern.

Fig. 3 also shows the location of parameters used by Nordhaus and Stern. Nordhaus sets $\delta = 1.5$% p.a. and $\eta = 2.0$ while Stern assumes $\delta = 0.1$% p.a. and $\eta = 1.0$. Nordhaus puts less weight on future generations than Stern, and puts more weight on the poorest and hence the present generations in Q1 and Q2. Nordhaus' parameters favor the solid paths in both Q1 and Q2. Stern's parameters suggest indifference in Q1 and favor the solid path and hence the non-monotonic development in Q2 — similar to Nordhaus.

When analyzing subjects' use of AWF (H_{20}), the solid path in Q1 dominates the dashed path for all δ and α-values. This is because the concave utility function favors stable over variable consumption growth, and because the solid path has the more rapid growth in the near-term. Fig. 4 shows the indifference curve for Q2 giving the same *W*-values (Eq. (3)) for both paths over a wide set of α-values.[3] Choosing the dashed path in Q2 is consistent with having δ-values at or below the indifference curve. Contrary to the SWF and consistent with prior reasoning about the AWF, choosing the monotonic consumption path in Q2 can be consistent with having positive δ-values, even higher than Nordhaus' assumption for the SWF.

The questionnaire design avoids many of the problems associated with stated preference surveys.[4] The questionnaire could also be seen to represent an example of information provided for policy debate and decision-making. As such, the questionnaire will indicate to what extent ordinary people are able to deal with time graphs of policy consequences.

The two questions were part of an online survey performed by YouGov[5] in the U.K. from 22 to 24 March 2011. Respondents were drawn from a well-balanced sample of the adult U.K. population (N = 2305). Efforts by YouGov to correct the results for minor imbalances in the composition of the sample only led to corrections of about one percentage point in frequencies. The analysis in this study is based on uncorrected data. For those who answered both questions, the median time spent was 8 min and 54 s. Ninety per cent of respondents spent more than 5 min and 17 s, and 99% spent more than 2 min and 56 s.

3.2. Second Questionnaire

Climate change is expected to have effects that stretch beyond the one hundred year time horizons in Q1 and Q2. Together with other resource limitations, long-term climate effects could seriously threaten sustainability. The Brundtland report (1987) raised concern about "the ability of future generations to meet their own needs". Still there is great uncertainty whether current policies lead to sustainable development or not (Arrow et al., 2004). There is also much disagreement as illustrated by the debate following the publication of "The Limits to Growth" (Meadows et al., 1972).

The second questionnaire addresses hypothetical scenarios over a five hundred year time horizon, see Fig. 5 and the Appendix A. The dashed line shows linear growth for hundred years followed by four hundred years of zero growth. Respondents choose between this dashed path and *each* of the solid paths in three consecutive questions Q3, Q4, and Q5. While the solid curve in Q2 portrayed a fluctuation, solid curves in Q3, Q4, and Q5 represent overshoots without recovery, a more severe type of unsustainable development.

All solid paths overshoot after having been higher than the dashed path for the first hundred years. While the dashed path ends up at 200 units, the solid paths end up at respectively 193, 156, and 70 units for Q3, Q4, and Q5 after having peaked at 200 units. Different from Q1 and Q2, paths are said to represent "well-being per person — reflecting private consumption, public services, and services provided by nature." The importance of the latter for integrated assessment models is demonstrated by (Hoel and Sterner, 2007) and (Sterner and Persson, 2008).

The purpose of the second questionnaire is to see how these types of overshoots influence implicit discount rates. Note that the solid path in Q3 dominates the solid path in Q4, which in turn dominates the one in Q5 whether welfare is measured by the SWF or the AWF. Thus, these three scenarios should not produce choices that lead to rejection of any of the two hypotheses.

Fig. 6 shows indifference curves for SWF when choosing between the dashed and each of the solid paths. The curves are quite insensitive to the value of η. Choosing the solid path in each of the three questions is consistent with having utility discount rates lower than the respective indifference curves. The scenarios are constructed such that Stern's parameters imply indifference between the dashed and the solid path in Q3. Nordhaus' parameters imply indifference in Q5. Q4 represents an in-between scenario to get a somewhat more detailed idea about the distributions of discount rates.

Fig. 7 shows indifference curves for the AWF over a wide set of α-values. Similar to Q2 and consistent with prior reasoning, indifference utility discount rates are higher for the AWF than the SWF. Related to the longer time horizon, upper limits for discount rates for the AWF are lower in Q3, Q4, and Q5 than in Q2.

Respondents were recruited from a class of first semester master students with varied backgrounds and representing many different nations (N = 52). To compare this group to the much larger UK sample in

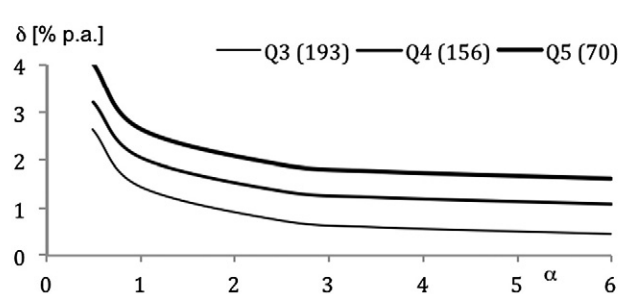

Fig. 7. Indifference curve for AWF for Q3, Q4, and Q5.

[3] For α-values above 3, the utility function is nearly linear over the range of yearly growth rates used in the scenarios.

[4] The embedding effect and failure to recognize budget constraints (Diamond and Hausman, 1994) should not apply because questions Q1 and Q2 pertain to *total* per capita consumption. Wording could inadvertently influence responses. An attempt has been made to come up with a conservative design; see the exact wording.

[5] YouGov, 50 Featherstone Street, London EC1Y 8RT, http://www.yougov.com/.

Table 1
Frequency of answers related to respective indifference curves in Fig. 3.

	Q1			Q2		
Relative to indifference curve	Lower	Equal	Higher	Lower	Equal	Higher
Frequency (%)	15.7	20.9	63.5	63.4	14.9	21.7

the first questionnaire, the second group answered Q1 and Q2 before answering Q3, Q4, and Q5.

4. Results

4.1. First Questionnaire

Raw data are available from the author. The ensuing analyses focus on the 1725 respondents (75%) that answered both Q1 and Q2. Table 1 gives an overview of the results. In Q1, 84.3% chose the solid curve consistent with a δ equal to or higher than the upper indifference curve for the SWF (solid or indifferent). The percentage is significantly greater than 82.8% (binomial test at the 5%-level). Thus, a clear majority chose responses consistent with a *consumption* discount rate equal to or higher than 1.78% p.a.

In Q2, 78.4% chose the dashed curve consistent with a δ equal to or lower than the lower indifference curve (dashed or indifferent), significantly greater than 76.7%. Thus, a clear majority chose responses consistent with a *consumption* discount rate equal to or lower than minus 1.30% p.a.

Among the 84% of individuals that chose the solid curve in Q1, 76.8% (significantly greater than 74.9%) chose the dashed curve in Q2, see Table 2. If they behaved according to the SWF, they must have reduced their utility discount rate from being above the upper indifferences curve to being below the lower one when going from Q1 to Q2. Similarly, it is also likely that many of the remaining 23.2% reduced their utility discount rates when going from Q1 to Q2. However, their adjustments were not large enough to favor the dashed development in Q2. Hence, between 75 and 100% of respondents in the majority group appear to change their preferences towards lower discount rates when going from Q1 to Q2. A similar tendency cannot be ruled out for the minority group with 16% of the subjects.[6] H_{10} can be rejected.

Regarding the AWF, in Q1 only 16% clearly distinguished themselves from the alternative predicted by the AWF.[7] Hence a clear majority seems to behave consistent or nearly consistent with the AWF. H_{20} cannot be rejected. In Q2, 78.4% chose consistent with a utility discount rate at or below the indifference curves in Fig. 4. In this case, negative utility discount rates are not needed to explain choices; a result that seems consistent with prior ideas about time preferences. H_{20} cannot be rejected.

4.2. Second Questionnaire

Raw data are available from the author. Of the 52 respondents, one subject did not answer all five questions. Six respondents gave answers to Q3, Q4, and Q5 that were not consistent with dominance. Most likely they would have changed their responses after being made aware of

Table 2
Number of choices relative to the upper and lower indifference curves for Q1 and Q2 in Fig. 3.

		Q1	
		$\delta \geq$ upper	$\delta <$ upper
Q2	$\delta >$ lower	338	36
	$\delta \leq$ lower	1117	234

dominance. These respondents were not included in the below analysis. Conclusions would not change if they were.

The second group differed somewhat from the UK sample. In Q1, 64.4% answered consistent with a utility discount rate at or higher than the upper indifference curve for the SWF, compared to 84.4% in the UK sample (significantly different at the 1% level). In Q2, 88.9% answered consistent with a utility discount rate at or below the lower indifference curve, compare to 78.3% in the UK sample (significantly different at the 4% level). The differences do not lead to different conclusions. The student group tends to value the long-term somewhat higher than the UK respondents.

Regarding the SWF, first consider implicit utility discount rates for Q5, Q4, and Q3 for Nordhaus' assumption about the consumption elasticity, $\eta = 2.0$. Combining Fig. 6 and Table 3, it is seen that 8.9% have an implicit utility discount rate higher than Nordhaus' assumption of $\delta = 1.5$. Only 2.2% have δ-values in the range from 0.81 to 1.5% p.a.; 17.8% have δ-values in the range from 0.0 to 0.81% p.a.; 2.2% have a δ equal to 0.0% p.a.; and 68.9% have a δ below 0.0% p.a. Clearly, the average implicit discount rate is significantly different from Nordhaus' assumption.

Next, consider implicit utility discount rates at Stern's assumption about the consumption elasticity, $\eta = 1.0$. At this η-value, the three δ-values denoting indifference are 1.43, 0.91, and 0.10% p.a., of which the latter coincides with Stern's assumption. The spread of implicit discount rates is the same as for Nordhaus' assumption about η. While a majority makes use of lower discount rates than Stern, we cannot conclude from these data that the average discount rate is significantly different from Stern's assumption.

Regarding the AWF, for $\alpha = 2.5$, the three δ-values denoting indifference are 1.91, 1.38, and 0.75% p.a. For $\alpha = 1.0$, the three δ-values denoting indifference are 2.66, 2.08, and 1.46% p.a. Again the spread of implicit discount rates is the same as above. For α-values in the range from 1.0 to 2.5, the majority has an implicit discount rate below an upper limit ranging from 1.46 to 0.75% p.a. This is considerably lower than the upper limit for δ in Q2, Fig. 4. The data are not sufficiently detailed to claim significant difference between average implicit discount rates in the first and the second questionnaire. However, it is an interesting question for further research to see if the implicit discount rate drops with the time horizon.

Regarding people's ability to choose between policies, choices in Q3, Q4, and Q5 seem consistent with choices in Q2. Of those that chose the dashed path in Q2, respectively 74, 92, and 95% chose the dashed paths in Q3, Q4, and Q5. Among those that chose the solid path in Q2, respectively 80, 40, and 40% chose the solid paths in Q3, Q4, and Q5. For choices of both dashed and solid in Q2, percentages change in the expected directions as the discrepancy between dashed and solid increases from Q3 to Q5. Hence, people seem to be able to make consistent choices.

5. Discussion

5.1. The Deterministic Case

When choosing between monotonically increasing consumption paths, Q1 suggests that SWF is appropriate, even when used with consumption discount rates that reflect current rates of return, as assumed by Nordhaus. Q2 reveals that people dislike overshooting and fluctuating

[6] Among the 16% of respondents in Q1 that chose answers consistent with a δ value below the upper indifference curve, 87% (significantly greater than 82%) made a choice in Q2 consistent with a δ value equal to or below the lower indifference curve. It seems likely that many in this group also lowered their implicit discount rate when going from Q1 to Q2. Although less likely, this could also have been the case for some of the 13% of respondents in this group who preferred the non-monotonic consumption path in Q2.

[7] The 21% who found both alternatives in Q1 equally good, do not count heavily towards rejection of the hypothesis since the welfare of the two consumption paths differ quite modestly. For α in the range from 0.5 to 2.0 and δ in the range from 0.1 to 1.5% p.a., differences between the criterion values for the two consumption paths fall in the range from 3.6 to 7.2%.

Table 3
Frequency of answers related to respective indifference curves in Figs. 6 and 7.

	Q3			Q4			Q5		
Relative to indifference curve	Lower	Equal	Higher	Lower	Equal	Higher	Lower	Equal	Higher
Frequency (%)	68.9	2.2	28.9	88.9	0.0	11.1	91.1	0.0	8.9

consumption developments and more so than what is implied by assumptions made by both Nordhaus and Stern. Importantly, one and the same SWF cannot explain subject choices in both Q1 and Q2. Subject responses imply that H_{10} should be rejected. The SWF theory could be saved by an auxiliary hypothesis saying that parameters vary with consumption scenarios. However, this would complicate analysis.

Aversion to overshoots and fluctuations is also likely to be in effect when consumption does not recover after an overshoot. Such a situation could occur if a stagnating or slowly growing economy (for other reasons than climate change) is negatively affected by worsening climate conditions. For such a case, questions Q3, Q4, and Q5 reveal average implicit utility discount rate for the SWF close to Stern's assumption of 0.1% p.a. and significantly lower than Nordhaus' assumption.

The potential problem of unsustainable development has led to several proposals to improve the SWF. One option is hyperbolic discounting, where the discount rate decreases over time (Kirby, 1997). This idea is supported by the use of questionnaires. However, related to the choice in Q2, all positive and declining utility discount rates favor the non-monotonic development. Another alternative is the rank-discounted utilitarian approach (Zuber and Asheim, 2012). This criterion most aggressively discounts the wealthier generations and thus has attractive fairness properties. However, for positive rank utility rates, this criterion also favors non-monotonic development in Q2.

The AWF with one set of parameters did predict correctly majority choices in all five questions. As predicted by prior reasoning, the AWF allows for somewhat higher utility discount rates that the SWF. While promising, further research is needed to check for potential weaknesses of the AWF and to establish parameters that reflect people's preferences. Inspired by the literature on ‘naturalistic decision making’ (Lipshitz et al., 2001), research on welfare functions should focus on very-long-term developments of consumption or well-being. Previous research shows that the time horizon matters for discount rate estimates (Frederick et al., 2002). For analysis, it seems less problematic to adjust discount rates to fixed time horizons than to consumption scenarios that vary with outcomes of random variables. Also, it seems interesting to explore the choice between relative and absolute growth in the AWF.

Because of complexity and the potential for subjectivity, general agreement on the superiority of one particular welfare function is unlikely. Agreement on one set of parameters is also unlikely. Even those who insist on basing the consumption discount rate on market rates of return face a challenge. The SWF requires two parameters, δ and η. The Ramsey equation provides a relationship between these two parameters and the consumption discount rate derived from the market rate of return.[8] Since there are two unknowns in this equation, a prior estimate must be used for one of them. Since prior estimates are highly uncertain,[9] values of δ and η come to vary over a wide range. This uncertainty is important because optimal policies can be sensitive to the resulting combination of δ and η. The same is the case for AWF; optimal policies are in general sensitive to the combination of δ and α.

Realizing major challenges, Koopmans (1965, p.226) noted: “… the problem of optimal growth is too complicated, or at least too unfamiliar, for one to feel comfortable in making an *entirely* a priori choice of an optimality criterion before one knows the implications of alternative choices. One may wish to choose between principles on the basis of the results of their application.” Hence, Koopmans suggests that focus should be on results, in this case on the consumption paths that follow from policies.

Policy alternatives can be derived in different ways. First, Koopmans suggested a trial-and-error approach where the *criterion* is iterated until an optimal policy results that gives a desirable consumption development over time. According to the above analysis, iterations should not be confined to parameter values; they should also include functional forms of criteria such as the SWF and the AWF. Second, one could shortcut Koopmans' procedure by iterating *policies* directly in simulation models until desirable developments over time result. For this purpose, formulating a welfare function is not needed; analysts judge the promise of policies by inspecting simulated time developments. Third, analysts could simulate policies *proposed* by policy-makers to see how these more intuitively based policies perform compared to those that result from formal analysis.

The above should not be read to say that analysts are the ones to choose between policies. Their role is to develop models, identify policies, and show policy consequences in terms of time developments, ideally in competition with other analysts. The questionnaires show that most people are both willing and able to make judgments and choose among policies. Choices were significantly different from random and did show considerable amounts of consistency. Information and debate could, and should, help correct possible framing effects.

Importantly, this procedure and role of analysts is different from current practice where policy makers are presented with policies that follow from optimization and welfare functions that Koopmans claimed to be “too complicated”. The wide spread in recommended GHG taxes suggests that complexity allows for subjectivity. Neither Nordhaus nor Stern shows paths of per capita consumption or other indicators of well-being. If they had, focus of the debate would probably have shifted away from discount rates and towards questioning the quality of the underlying assessment models.

Stern reports on three methods to analyze climate policies. The two first methods give reasons for strong policy measures; the third method considers the economics of these policies. Stern uses the simulation model PAGE where: “…policies are specified by the user, and PAGE calculates their implications” (Hope et al., 1993, p.328). Having made use of simulation, Stern could have presented policy implications in terms of time developments. However, Stern uses the SWF to find the social costs of GHG emissions and hence GHG tax rates. Stern's low values of δ and η make the policy recommendations from the two first methods appear economical (near optimal). Since Stern does not show time developments for consumption, it is difficult to judge the reasonableness of his parameter assumptions in light of the above findings.

In his DICE model Nordhaus uses intertemporal optimization to find optimal taxes on greenhouse gases and to find optimal global investments. In this case both the tax policy and the social cost of GHG emissions follow from the SWF and its parameters. Within this framework Nordhaus argues that to be consistent, the consumption discount rate

[8] The Ramsey equation expresses the *consumption* discount rate as $\rho_t \approx \delta + \eta g_t$ where g_t denotes growth of consumption at time *t*. An estimate of δ can be found from a prior estimate of η and by setting ρ_t equal to an estimate of the market rate of return.

[9] For instance, Atkinson et al. (2009) point out that η reflects preferences over three dimensions: risk, inequality in space, and inequality in time. Theoretical arguments hold that measures of these three concerns should be strongly related. However, empirical investigations show that “correlations between attitudes to risk, inequality and intertemporal substitution are weak” (p.1). This provides one possible explanation for why empirical estimates of η have varied “all the way from 0 to 10” (p.3).

must be equal to the current market rate of return.[10] If a different consumption discount rate were used in the DICE model, it would have important implications for savings rates and current investments. To point out inconsistency in Stern's analysis, Nordhaus writes: "[t]o a first approximation, the Review's assumptions about time discounting and the consumption elasticity would lead to a doubling of the optimal global net savings rate" (p. 694). While this is correct within Nordhaus' optimization model, it does not follow that Stern's GHG tax would lead to a doubling.

By implementing Stern's GHG tax in a macroeconomic simulation model or in the real economy, short- and medium-term economic growth would most probably be somewhat reduced. The same would be the case for savings rates and investments. There would be no doubling. An historical example illustrates this point. To maintain long-term biodiversity, the International Whaling Commission banned commercial whaling in 1986. To justify such a ban on economic grounds, they would have had to apply a discount rate much below the current market rate of return (Clark, 1973). The policy had indistinguishable effects on global investments.

Hence the challenge for policy makers is to identify *special-purpose* policies to prevent climate change as well as other undesired very-long-term developments. Similarly, special-purpose policies could be used to encourage investments in long-lived dams for hydro electricity, infrastructure, and other means to ensure long-term sustainability. The discount rate is not a *general-purpose* policy instrument as long as there is a risk of non-monotonic growth. This said, when special purpose policies are in place to deal with very-long-term issues, the market rate of return will be a proper indicator for the discount rate to be used for all decisions that are of little consequence for very-long-term developments.

Dasgupta (2008) reaches a related conclusion when saying that in a fully optimizing economy it is appropriate to discount future consumption at market rates of return. In the context of the present paper, "fully optimizing" should be interpreted to mean an economy with special-purpose policies to prevent overshoots and unsustainable developments.

5.2. The Case of Uncertainty

The deterministic case resolves much of the current controversy over discounting. The next step is to consider uncertainty. Standard methods are problematic.[11] First, there is a need for better models that allow for rare events and that capture complex dynamics. Second, the search for policies calls for optimization models with robust welfare functions. Third, new methods are needed to portray policy consequences over time.

Stocks, feedback processes, and uncertainty complicate the search for good policies. Optimization theory provides insights (Bertsekas, 1987). In infinite horizon stochastic models, yearly decisions should in general be nonlinear *functions* of all current stocks. Hence, the GHG-tax in any year should be a feedback policy of important stocks. Measurement error implies that both current and recent measurements of stock levels should be considered in order to filter out noise. Parameter error implies that updated (recursive) parameter estimates should influence decisions. That is, decisions today should take into consideration that over time one will have more precise information and that future decisions will be adapted to the new information.

For *given* policy functions, Monte Carlo simulations present an interesting alternative to explore policy consequences. A challenge in this case is to find ways to present developments over time. Thousand simulated developments in one graph tend to be messy. Presenting percentiles for each and every year could mask fluctuating paths. Using software to count the number of paths that fall into certain behavior groups would be more useful. That would give analysts and decision-makers a sense of probabilities of overshooting relative to monotonic developments and of high relative to low consumption levels.

Uncertainty complicates and makes it more desirable to make use of optimization to identify policies. On the other hand, high complexity makes it impossible to find fully optimal policies. However, the less ambitious task of policy improvement is still an option. Using Monte Carlo simulations, software can search for *parameters* in flexible policy functions that maximize a welfare function (Powersim, 2013). Such optimization in policy space has provided policy improvement in complex problems with measurement error (Moxnes, 2003) and with parameter uncertainty (Moxnes, 2010). Stochastic optimization in policy space requires a welfare function that captures *expected* welfare. In practice this is obtained by calculating average welfare over all Monte Carlo runs for a given policy. For this purpose the AWF seems more robust than the SWF.

How does the above approach compare to Nordhaus' and Stern's methods? Nordhaus operates with a deterministic model such that his recommendations do not reflect uncertainty. Stern uses the PAGE model with the SWF and Monte Carlo simulations to study the effects of uncertainty in more than 30 parameters. With quite symmetric distributions around expected parameter values, and a concave utility function ($\eta = 1$), uncertainty leads to reduced utility. Hence, uncertainty increases the present social cost of climate change and calls for higher GHG taxes than that resulting from a deterministic scenario.

The above approaches are complex and it is tempting to retract to the simpler approach indicated by Pindyck (2013): "Perhaps the best we can do is come up with rough, subjective estimates of the probability of a climate change sufficiently large to have a catastrophic impact, and then some distribution for the size of that impact…" Hence, if analysis finds that the probability of catastrophic runaway climate change is unacceptably high, further analysis could be reduced to study least-cost strategies to reduce GHG emissions well below safe upper limits (Ackerman et al., 2009; Pindyck, 2013). Currently, there does not seem to be convincing evidence of sufficiently large catastrophic impacts to agree on some least-cost strategy. Without such evidence, there is need for advanced model studies of policies to avoid potential overshoots in consumption or well-being.

6. Conclusions

Controversy over discounting is likely to weaken the impact of economic analysis of climate policies and of policies for sustainable development. This is worrisome because without good understanding, people tend to favor intuitively appealing wait-and-see strategies (Sterman, 2008; Moxnes and Saysel, 2009). Controversy follows from optimization and use of intertemporal welfare functions that Koopmans (1965) claimed to be "too complicated". A natural question arises; could one do without welfare functions and discounting when choosing between policies? Using two questionnaires it is found that when people are presented with graphs of policy consequences over time (per capita consumption or well-being), they are able to make consistent choices. The paper also offers some ideas for how uncertainty could be captured in such graphs.

Policy alternatives can be based on intuition, follow from simulation studies, or result from optimization. The latter method requires the use of welfare functions. The first questionnaire finds that the standard (social) welfare function (SWF) explains well people's choices among steadily increasing consumption paths, with implicit discount rates similar to market rates of return. However the very same SWF is not able to capture people's aversion to overshoots and fluctuations. The second questionnaire finds that when long-term sustainability is threatened, people tend to use very low discount rates. Among the respondents, 91% choose as if they use the SWF with a utility discount rate lower

[10] As justification for this assumption Nordhaus points to the likely behavior of individual countries bargaining about emission reductions. However, this argument does not hold from a normative point of view. When confronted with a global commons problem, nations should aim for perfect cooperation and not Nash equilibrium.

[11] According to Weitzmann (2007, p.704) "…standard approaches to climate change (even those that purport to treat uncertainty) fail to account fully for the implications of large consequences with small probabilities…" Dasgupta (2008, p.167) concludes: "… if the uncertainties associated with climate change losses are large, the formulation of intergenerational well-being we economists have grown used to could lead to ethical paradoxes even when the uncertainties are thin-tailed: an optimum policy may not exist."

than Nordhaus' assumption of 1.5% p.a. A remarkable 71% reveal a discount rate close to or below Stern's assumption of 0.1% p.a.

It follows that it is problematic to use the SWF to search for optimal policies unless fluctuating or overshooting consumption paths can be ruled out. Ruling out such behaviors is particularly difficult in models that capture uncertainty; a complication that increases the relative advantage of optimization when searching for policies. For this purpose, an alternative welfare function (AWF) reflecting per capita consumption growth is found to be largely consistent with subjects' choices in both of the two questionnaires.

To resolve the controversy between Nordhaus and Stern, more thorough studies of the potential for overshoots and unsustainable developments are needed.

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Appendix A

A.1. Questionnaire 1

Respondents received the following text (figures are shown in the main body of the paper and all questions have the same wording and are not repeated):

Imagine that you are going to participate in a referendum about governmental policies that will influence consumption development over the next one hundred years. Think of consumption as the sum of private consumption and public services. You get no information about what the policies are. However, you will see the exact consequences of the policies on national consumption development per person.

Your personal consumption will develop in pace with national consumption. When choosing between consumption developments, pay close attention to how consumption develops over your expected lifetime. You may also consider the future consumption of your own and friends' children and grandchildren. Be honest about how much of your own consumption you are willing to give up for children and grandchildren that will enjoy higher consumption than you.

The effects of two different consumption development policies are shown as *Solid* and *Dashed* lines on the below graph. [Fig. 1 in article]

Solid shows steady growth and in the last year consumption is 4 times higher than in 2010. *Dashed* also shows steady growth, however, it has lower consumption than *Solid* until 2057, after that *Dashed* gives the higher consumption. After year 2110, the two consumption developments are equal.

Q1: Which of the developments, *Solid* or *Dashed*, do you prefer?

I prefer *Solid* development

I prefer *Dashed* development

I find both developments equally good

I cannot answer the question

Like in the previous question, the effects of two different consumption development policies are shown as *Solid* and *Dashed* lines on the below graph. [Fig. 2]

Dashed shows steady growth such that in the last year consumption is 4 times higher than in 2010. *Solid* does not show steady growth, and shows a decline in consumption for a 12 year long period after 2045. However, *Solid* does give higher consumption than *Dashed* until 2052, after that *Dashed* has the higher consumption. After year 2110, the two consumption developments are equal. [Q2: same wording as Q1]

A.2. Questionnaire 2

Respondents first answered Questionnaire 1; then they went on to Q3.

Q3. Like in the previous questions, the effects of two different policies are shown as *Solid* and *Dashed* lines on the below graph.

Note however that in this case the time horizon is extended to *500 years*. Think of the paths as representing *well-being per person* — reflecting private consumption of goods and services, public services, and services provided by nature.

[Fig. 5 in paper with the dashed and the solid curve for Q3 only]

Dashed shows growth along a straight line until well-being doubles after 100 years. After that, *Dashed* is constant and equal to *200 units*. *Solid* grows faster than *Dashed* to begin with. Then it grows more slowly than *Dashed* towards 200 units. After 100 years, *Solid* declines for about twenty years and ends up at *193 units* for the rest of the time. [Q3: same wording as Q1]

Q4. This question is identical to Q3 except that *Solid* ends up at *156 units* rather than *193 units*.

[Fig. 5 in paper with the dashed and the solid curve for Q4 only]

Dashed shows growth along a straight line until well-being doubles after 100 years. After that, *Dashed* is constant and equal to *200 units*. *Solid* grows faster than *Dashed* to begin with. Then it grows more slowly than *Dashed* towards 200 units. After 100 years, *Solid* declines for about sixty years and ends up at *156 units* for the rest of the time. [Q4: same wording as Q1]

Q5. This question is identical to Q4 except that *Solid* ends up at *70 units* rather than *156 units*.

[Fig. 5 in paper with the dashed and the solid curve for Q5 only]

Dashed shows growth along a straight line until well-being doubles after 100 years. After that, *Dashed* is constant and equal to *200 units*. *Solid* grows faster than *Dashed* to begin with. Then it grows more slowly than *Dashed* towards 200 units. After 100 years, *Solid* declines for about hundred and ten years and ends up at *70 units* for the rest of the time. [Q5: same wording as Q1]

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