Disentangling the Stern/Nordhaus Controversy: Beyond the Discounting Clash

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Abstract

The Stern/Nordhaus controversy has polarized the widely disparate beliefs about what to do in order to tackle the climate challenge. In order to explain differences in results and policy recommendations, comments following the publication of the Stern Review have mainly focused on the role played by the discount rate. A closer look at the actual drivers of the controversy reveals however that Stern and Nordhaus also disagree on two other parameters: technical progress on abatement costs and the climate sensitivity. This paper aims at appraising the relative impacts of such key drivers of the controversy on the social cost of carbon and climate policy recommendations. To this end, we use the flexible assessment model RESPONSE which allows us to compare very diverse worldviews, including Stern and Nordhaus'ones within the same modelling framework and map the relative impacts of beliefs on the three key drivers of the controversy. Furthermore we appraise quantitatively, by means of a linear statistical model, the impacts on results of an extended set of core parameters of RESPONSE. We show that beliefs on long term economic growth, technical progress, the form of the climate damage function and the climate sensitivity outweigh the impact of pure time preference on results. Hence, we can qualify the role played by the discount rate in the Stern/Nordhaus controversy and more broadly in the definition of climate policies.

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1 Introduction

There is now a consensus among climate economists to consider climate change as a global externality that must be compensated for to recover economic optimality. Hence, basic public economics wisdom requires some mitigation efforts (IPCC, 2007). The issue gets controversial however when we try to answer the “when” and “how much” questions. In a nutshell, the dynamic puzzle arising from a long-standing debate originated in the early 1990s, is about whether we should act strongly now or gradually and later. Those two polar climate policies could be referred to as the Stern (2006)/ Nordhaus (2008) controversy. While Stern promotes sharp early abatement as a precautionary measure to prevent potential future catastrophic damage, Nordhaus argues that it is more economically sound to postpone abatement efforts (following a so-called “policy-ramp”) and tolerate higher potential climate risks given that those risks would be better borne by supposedly richer future generations than relatively poor present ones.

Fine tuning of mitigation efforts over time directly derives from the appraisal of society’s willingness to pay to tackle the climate issue. Within an optimal control framework, such willingness to pay should be equal to the value of the climate externality known in the literature as the Social Cost of Carbon (SCC). The computation of the SCC over the next century is a symmetric issue to the timing of action as the higher the SCC the higher the willingness to mitigate climate change. Computed along an optimal path of growth and carbon emission, the SCC is the value equating at each date the discounted sum of the marginal cost of abatement with the discounted sum of remaining marginal climate damages (Nordhaus, 2011; Pearce, 2003; Tol, 2008). This crude optimality rule makes it possible to delineate the efficient border of mitigation efforts.

Similarly to the timing dispute, there is no academic consensus about the value of the SCC and published literature provides very wide ranges of values. Indeed the most recent Intergovernmental Panel on Climate Change (IPCC) report gives a SCC range of $ – 3 ⇑ tCO_2 to $95 ⇑ tCO_2 (IPCC, 2007). Tol (2005) gathers 103 estimates and finds out that the median estimate is $4 ⇑ tCO_2, the mean $26 ⇑ tCO_2 and the 95 percentile $97 ⇑ tCO_2.

The debate following the Stern Review (Dasgupta, 2007; Nordhaus, 2007; Weitzman, 2007; Yohe and Tol, 2007) has reopened the “when/how much” controversy and eventually exacerbated irreducible differences in results and policy recommendations. This was due to a heavy focus on the discounting clash between Stern and Nordhaus’ approaches and a surprising disregard for the lessons learned from the 1990s in the so-called “when” flexibility controversy about the roles of inertia, uncertainty (Ambrosi et al., 2003; Ha-Duong et al., 1997; Manne and Richels, 1992), irreversibility Chichilnisky and Heal (1993); Kolstad (1996); Ulph and Ulph (1997); Ha-Duong (1998); Pindyck (2000), and learning (Goulder and Mathai, 2000). The alarmist results found by Stern would be mainly driven by the unusual low pure time preference (0.1%) retained in his model, while a more conventional rate (2%) would have given smoother “Nordhaus-like” results. Indeed, in a deterministic framework, it is easy to figure out how the rate of pure time preference may critically impact models’ results as it balances the relative value of future damage (that will mostly arise after 2050) against present costs of emission reductions. Then the higher the discount rate the lower the present value of discounted future damage. This insightful dispute has raised fundamental intergenerational ethical questions, while ruling out other critical drivers of the controversy such as beliefs on climate damage, climate sensitivity[1], future economic growth, and abatement costs.

Building on the emblematic Stern/Nordhaus controversy, we disentangle the drivers of the controversy in order to explain the reasons for such wide differences in SCC and climate policy recommendations. We argue that Stern and Nordhaus do not only dramatically disagree on the pure time preference to pick, but also on two other critical parameters: climate sensitivity and the evolution of abatement costs. The calibration of those parameters basically rests on "beliefs" because there is no decisive argument to pick one value rather than another, and eventually the calibration results from an irreducible subjective choice within reasonable ranges provided by most advanced research. The combination of beliefs on these parameters constitutes what we call a "worldview".

This paper aims at appraising the relative impact on results of those three beliefs and qualifying the impact of pure time preferene. To carry out this analysis we use RESPONSE (Ambrosi et al., 2003; Perrissin-Fabert et al., 2009) which has the same basic modelling structure as DICE (Nordhaus' model) and PAGE (Stern's model) and thus makes it possible to compare Stern and Nordaus' worldviews within a unique consistent framework. In this analysis, the discount rate is no longer the keystone variable we have to agree on for implementing any climate policy. It is only a key variable among a broader set of at least three structural parameters including the climate sensitivity and the technical progress on abatement costs. RESPONSE allows us to map the relative impacts of beliefs on this three key parameters. In addition to this graphical disentangling of the controversy, we use a linear statistical model (find ref) to appraise quantitatively the relative impacts of core parameters of RESPONSE over time, such as the growth rate the forms of both the climate damage and abatement cost functions in addition to the three key drivers of the Stern/Nordhaus controversy.

In section 1 we present the controversy within the framework of RESPONSE. In section 2 we draw a mapping of the Stern/Nordhaus controversy that decomposes graphically the impacts of discounting, abatement costs and climate sensitivity on abatement and SCC trajectories. We run in section 3 a comprehensive sensitivity analysis on these three beliefs to get a significant number of scenarios. We apply to the grid of results an econometric analysis that makes it possible to provide quantitative estimates of the relative impacts on SCC and abatement levels of the parameters that make up a worldview. This allows us to show that beliefs on pure time preference do matter though their impact is often less important than beliefs on technological progress, the climate sensitivity or long term economic growth. We also believe that our approch could provide the climate debate with a useful transparent framework to better understand the impact of modelling choices on the SCC and climate policy recommendations.

2 The Stern/Nordhaus Controversy: Beyond the Discounting Clash

2.1 A comparison of Stern and Nordhaus' modelling frameworks

We examine in this section the differences between DICE (Nordhaus, 2008) and PAGE (Stern, 2006; Hope, 2006).

[1] The climate sensitivity is the temperature increase implied by a doubling of preindustrial level of CO_2eq concentration.

DICE and PAGE have very close modelling frameworks. They are both dynamic integrated assessment models that couple a macroeconomic optimal growth model[2] with a simple climatic model. Carbon emissions are considered as a fatal product of the production. They are responsible for temperature increase and thus for climate damage. As climate damage negates part of the production, the optimization process consists in allocating the optimal share of the output among consumption, abatement and investment, in order to maximize an intertemporal social utility function composed of the consumption of a composite good

They both use an isoelastic social utility function $UC = \frac{C^{1-\alpha}}{1-\alpha}$, with C the consumption of a composite good, and α the elasticity of marginal utility which is set at 2 in DICE and 1 (leading to $UC = logC$) in PAGE

They both account for a one-shot decision process and do not examine sequential decision-making

Stern and Nordhaus share a similar belief about long term economic growth (g = 1.3% per year over the next century)

The most striking difference between Stern and Nordhaus' worldviews lies in the choice of the rate of pure time preference. Based on the Ramsey's formula, the discount rate r writes: $r = \rho + \alpha.g$, with ρ the rate of pure time preference, g the rate of long term economic growth, and α the elasticity of the marginal utility of consumption. Nordhaus advocates a positive approach to determine ρ and suggests $\rho = 1.5\%$ in order to match an observed value of discount (or interest) rate of 4.1% ($1.5 + 2 \times 1.3 = 4.1$). Conversely, Stern makes the case for a normative settting of the rate of pure-time preference. He argues following Ramsey (1928); Sen (1961); Solow (2008) that the only legitimate argument for placing less value on the utility of future generations is the possible extinction of mankind in the future. Then, the ratio $\frac{1}{1-\rho^t}$ should be interpreted as a rough estimate of the probability of extinction of mankind making $\rho = 0.1\%$ the most sound choice[3]

Although Stern and Nordhaus consider the same ranges of values provided in IPCC reports to calibrate key parameters such as climate sensitivity and the evolution of mitigation costs, they differ in the choice of the value of the parameter within those ranges. Regarding climate sensitivity they both refer to the range [1.5 °C - 4.5 °C] given in (IPCC, 2007). While Nordhaus integrates in DICE the mean value of 3 °C, Stern deals with a so-called "high+" climate scenario (Stern Review Part II Box 6.2 p.156) in order to explore possible consequences of amplifying natural feedbacks that would rise climate sensitivity up to the range [2.4 °C - 5.4 °C] (Murphy et al., 2004). Instead of integrating a mean value into the model, he runs PAGE with the whole spectrum of values and then computes the 5 and 95 percentiles as well as a mean case to exhibit estimates of climate damages for instance[4].

Regarding the evolution of mitigation costs, Nordhaus has a rather pessimistic belief as he defines a backstop price (BK) at \$1,200 $_\Uparrow tCO_2$ in 2005 which barely decreases down to \$950 $_\Uparrow tCO_2$ in 2100. Conversely, Stern has a rather optimistic belief on technological progress. He does not set explicitly a backstop price but estimates that mean cost of mitigation will dramatically decrease from \$61 $_\Uparrow tCO_2$ (for an abatement level of 7.5%) in 2015 to \$22 $_\Uparrow tCO_2$ in 2050 (for an abatement level of 75%). His cost

[2] much like Ramsey-Cass-Koopmans' models (Ramsey, 1928; Koopmans, 1963; Cass, 1966).

[3] Indeed with $\rho = 0.1\%$, the probability of human race surviving 100 years is 0.905, while it turns out to be only 0.223 with $\rho = 1.5\%$ which looks, by far, too pessissimistic

[4] The calculation of these estimates are based on a probability distribution over the range of climate sensitivity which gives a greater weight to high values of climate sensitivity, with a 20% chance that climate sensitivity could be greater than 5 °C, in comparison to usual probability distributions

Table 1: Differences and similarities in Stern's and Nordhaus' models

	Nordhaus	Stern
Type of model	IAMs based on an intertemporal optimal growth model	
Utility function	$UC = \frac{C^{1-\alpha}}{1-\alpha}$, with $\alpha = 2$ in DICE, $\alpha = 1$ in PAGE	
Decision framework	One-shot decision	
Economic Growth	$g = 1.3\%$	
Climate dynamics	Simplified carbon and temperature dynamics	
Discount rate	$\rho = 1.5\%$ leading to $r_N = \rho + \alpha.g = 4.1\%$	$\rho = 0.1\%$ leading to $r_S = 1.4\%$
Abatement cost	$BK = \$1,200$ ⇑ tCO_2 in 2005, $BK = \$950$ ⇑ tCO_2 in 2100	Average cost of mitigation: from \$61 ⇑ tCO_2 in 2015 to \$22 ⇑ tCO_2 in 2050
Cimate sensitivity	3 °C as the mean value of [1.5 °C - 4.5 °C]	High+ climate scenario [2.4 °C - 5.4 °C] with a fat tail probability distribution
Damage	(1% - 5%] of GDP loss for a 4 °C increase	additional estimates including non market impacts.

estimates are mostly based on technological bottom up studies

Regarding climate damage, Stern and Nordhaus use a quite similar quadratic damage function as for a given level of increase in temperature, PAGE and DICE give close estimate of damage amounting to few percentage points of GDP (between 1% and 5% of GDP loss for a 4 °C increase). In addition to these "mainstream " damage estimates, Stern also provides more original estimates including non market impacts which roughly double climate damage.

While the controversy mostly focused on the discounting issue as it appears as the most obvious line of division between the two approaches, this comparison of Stern and Nordhaus' worldviews suggests that differences of beliefs on climate sensitivity and abatement costs may also have an impact on results. RESPONSE allows us to disentangle and map those impacts.

2.2 An introduction to RESPONSE

RESPONSE belongs to the same type of IAMs as DICE and PAGE, based on an intertemporal optimization of a growth model coupled with a climatic model.

The intertemporal maximization program between $t_0 = 2010$ and T (with $T = 2200$) simply writes:

$$V = \max_{A_t, C_t} \sum_{t=t_0}^{T} N_t \frac{1}{(1+\rho)^t} u\left(\frac{C_t}{N_t}\right),$$

where $u.$ is the standard logarithmic utility function, N_t is the population at t, which is assumed to grow at an exogenous rate, C_t is the consumption of a composite good at t, A_t is the abatement of emissions at t and ρ is the rate of pure time preference.

This program is solved under a set of constraints

The capital dynamics writes:

$$K_{t+1} = 1 - \delta K_t + Y K_t, L_t - C_t - C_a A_t - D\theta_{t,at},$$

where K_t is the capital at t, δ is the parameter of capital depreciation, L_t is an exogenous factor of labor (adjusted with exogenous technical progress) that enters Y the traditional Cobb-Douglas function of production, C_a, the abatement cost function, and D the quadratic damage function. Total amount of emissions abatement A_t lies in the range[0 - E_t], with E_t the level of emissions which simply writes: $E_t = \sigma_t Y K_t, L_t$, σ_t being the carbon intensity of production.

The abatement cost C_a depends on abatement A_t:

$$C_a A_t = \frac{1}{1+\gamma^{t-t_0}} A_t \zeta + BK - \zeta \frac{A_t^\nu}{\nu} E_t^{1-\nu}$$

The abatement cost is thus a sum of a linear function and a power function (with $\nu = 4$). The rate γ of technical progress in abatement technologies is exogenous. At $t = t_0$, ζ is the marginal cost of abatement when abatement is nul ($C'_a A_{t_0} = 0 = \zeta$), BK stands for the price of backstop technology, which is, by definition, the marginal cost of abatement when abatement amounts to emissions E_t ($C'_a A_{t_0} = E_{t_0} = BK$).

The quadratic damage function D writes,

$$D\theta_t, K_t = \chi \theta_t^2 Y K_t, L_t,$$

where θ_t stands for the increase in temperature in comparison to preindustrial temperature, and χ the curvature of the quadratic function.

The model also incorporates the linear three-reservoir model of carbon cycle by Nordhaus (Nordhaus and Boyer, 2003) and a temperature model resembling Schneider and Thompson's two-box model (Schneider and Thompson, 1981) in the same fashion as (Ambrosi et al., 2003; Nordhaus, 2008). At each step, temperature is a function of previous temperature and carbon stocks, and carbon stocks are functions of previous carbon stock and emissions after abatement ($E_t - A_t$)[5].

2.3 The Stern/Nordhaus controversy reframed by RESPONSE

Our analysis of the differences between DICE and PAGE has pointed out that three main beliefs distinguish Stern and Nordhaus' worldviews: the rate of pure-time preference, abatement costs and climate sensitivity. We now show how we integrate their differences in beliefs in RESPONSE:

Pure-time preference rate The discount rate amounts to 4.1% in Nordhaus' setting and 1.4% in Stern's one. As RESPONSE uses a logarithmic utility function, the elasticity of the marginal utility of consumption is set to 1 (as in PAGE) instead of 2 as in DICE. Then to recover the same overall discount rate as in DICE we are obliged to inflate the parameter of pure time preference up to 2.8. This operation is justified as Nordhaus (2008) asserts that alternative calibrations of consumption elasticity and pure time preference are allowed as long as they lead to the same real interest rate (or discount rate).

[5] For a full description of the climate dynamics, see working paper cired

Abatement costs Nordhaus specification of abatment cost are readily put into RESPONSE. As suggested in (Nordhaus, 2008) we choose BK to be \$1,200/tCO_2 in 2005 and a annual rate of technical progress of $\gamma = 0.0025\%$ over the next century in order to reach a backstop cost of \$950/tCO_2 in 2100. We choose $\zeta = \$0$/$tCO_2$ as abatement function in DICE is a power function which does not integrate any linear part. For the Stern-like setting of the abatement function, we decide to take the same backstop price $BK = \$1,200$/$tCO_2$ in 2005 and calibrate the other parameters (γ and ζ) of the function so that they fit with Stern's belief on mean cost of mitigation in 2050. Mean cost MC writes:

$$MCA_t = \frac{C_a A_t}{A_t} = \frac{1}{1+\gamma^{t-t_0}} \; \zeta + BK - \zeta \frac{A_t^{\nu-1}}{\nu} E_t^{1-\nu} \; .$$

As A_t is a fraction of E_t, we can replace A_t with aE_t, with a the level of abatement expressed as a fraction of emission (i.e. $a \in (0-1]$). This leads to:

$$MCA_t = \frac{1}{1+\gamma^{t-t_0}} \; \zeta + BK - \zeta \frac{a^{\nu-1}}{\nu} \; .$$

Then we solve a system of two unknowns two equations given that, according to Stern mean cost of abatement decreases from \$61/tCO_2 in 2015 for an abatmement level (a) of 7.5 percent to \$22/tCO_2 in 2050 for an abatement level of 75 percent, and eventually get the annual rate of technical progress $\gamma = 0.0522$ and the linear cost $\zeta = \$101$/$tCO_2$ in 2005.

Climate sensitivity We choose a climate sensitivity of 3 °C for Nordhaus as he explicitly retains this value in DICE. For Stern, we use the "high+" range of climate sensitivity [2.4 °C - 5.4 °C] to determine his climate sensitivity. The only information we have about the probability distribution over this range is that the mode is 3.5 °C and there is a 20% chance that climate sensitivity could be greater than 5 °C. We then set Stern's climate sensitivity at 4 °C. This difference in climate sensitivity leads to higher temperature increase for the same level of emission so that with the same BAU emission scenario climate damage hits almost 4% of total wealth in 2100 in the Stern's approach while it amounts to 2.5% of GDP in DICE.

To account for the Stern/Nordhaus controversy, we thus calibrate RESPONSE with two sets of beliefs as described in Table 2.

3 Mapping the Relative Impacts of Key Drivers of the Controversy

As Stern and Nordhaus mainly disagree on three parameters which can take two values each, we run RESPONSE with eight ($= 2^3$) possible sets of parameters. Inside the space defined by the two polar Stern/Nordhaus worldviews there are thus six other scenarios corresponding to a mix of Stern and Nordhaus' beliefs on the discount rate, climate sensitivity, and abatement costs.

To recognize the underlying beliefs of a given worldview we define the graphical code presented in table 3.

Table 2: The three variables accounting for Stern and Nordhaus' differences in worldviews

	Nordhaus	Stern
Pure time preference	ρ = 2.8%	ρ = 0.1%
Abatement cost in 2005	$BK = \$1,200 \Uparrow tCO_2$ with low rate of decrease (γ = 0.25% per year) and no initial marginal cost ζ = $\$0 \Uparrow tCO_2$	$BK = \$1,200 \Uparrow tCO_2$ with high rate of decrease (γ = 5.22% per year) and an initial marginal cost ζ = $\$101 \Uparrow tCO_2$
Climate sensitivity	3 °C	4 °C

Table 3: Graphical code used in figure 1

○ or ●	low climate sensitivity
▲ △	high climate sensitivity
● or ▲	high ρ
○ or △	low ρ
-○- and -△-	fast technical progress
○ and △ without line	slow technical progress

3.1 Analysis of abatement and SCC trajectories

We first present in figure 1 trajectories of abatement and SCC over the period 2010 - 2130. The two charts on the left side of the figure only compare Stern and Nordhaus' results while the two charts on the right side compare the eight worldviews at the same time.

Stern and Nordhaus' abatement profiles differ radically. While Stern's optimal path consists in decarbonizing the economy in a very short period of 50 years between 2020 and 2070, Nordaus' results are much smoother with abatement effort starting in 2010 at 16 percent and then slightly increasing till 2130 up to 25.5 percent. Extending the comparison to the six other worldviews makes it possible to point out the impact of beliefs on abatement profile. Starting from the Stern profile, it happens that increasing the rate of pure time preference and /or reducing the value of the climate sensitivity does not change qualitatively the form of the abatement path. Full decarbonization is still reached in a short period of fifty years, while the very moment of mitigation efforts take-off is postponed so that abatement only starts in 2050 for instance when pure time preference is high and climate sensitivity is low. The trend of abatement changes dramatically however when beliefs on abatement costs shift from the Stern's setting of the abatement cost function to the Nordhaus'one. Indeed, in all cases with a low rate of technical progress mitigation efforts start since 2010 and keep increasing gradually over time. Pure time preference and climate sensitivity mostly impact the initial level of abatement[6].

[6] The higher the climate sensitivity the higher the initial level. Conversely, the higher the rate of pure time preference, the lower the initial level of abatement

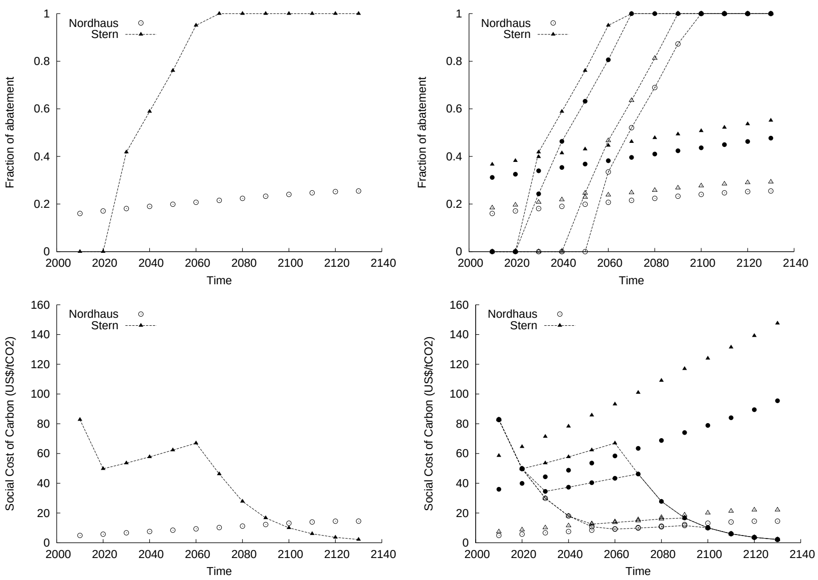

Figure 1: Abatement and SCC trajectories from 2010 to 2130 for Stern and Nordhaus only first and then for the six other possible worldviews resulting from a combination of Stern and Nordhaus' beliefs. Empty circles with no line stand for Nordhaus trajectories. Full triangles with lines stand in turn for the time profile of the Stern's optimal position.

Regarding SCC trajectories, the interpretation of Nordhaus' results is quite straightforward. The SCC follows an increasing trend in relatively low ranges of values from \$5 ⇑tCO$_2$ in 2010 up to \$14.5 ⇑tCO$_2$ in 2130 which directly result from the smooth trend of the mitigation path. In the Stern case however the SCC does not follow the same path as mitigation efforts. By 2020, as abatement efforts have not yet started then the SCC is only driven by the linear cost ζ which equals \$101 ⇑tCO$_2$ in 2005 and decreases at the annual rate $\gamma = 5.2\%$. The SCC in this period can be interpreted as the willingness to pay for R&D efforts in mitigation technologies preceding the launching of the low-carbon transition of the economy. Hence the SCC first decreases between 2010 and 2020 from \$83 ⇑tCO$_2$ to \$50 ⇑tCO$_2$. Then it starts increasing when abatement efforts begins and keeps increasing strongly during the decarbonization period from \$50 ⇑tCO$_2$ to \$67 ⇑tCO$_2$. When abatement reaches 100 percent then the SCC equals the price of the backstop technology at that moment and starts decreasing following the rate of technological progress on mitigation costs. As for the other hybrid worldviews, we notice the same effect as in the abatement profiles: mitigation costs impact qualitatively the form of the trajectory, while pure time preference and climate sensitivity impact the level of the SCC around the two structural trajectories resulting from the two polar beliefs on mitigation costs.

3.2 The controversy in the abatement/SCC space

In figure 2 we plot the results in a two-dimensional space with abatement on the x axis and the SCC on the y axis. Any point in this space stands for a position in the climate debate (expressed in terms of SCC and level of abatement) taken at thirteen consecutive dates (from 2010 to 2130), for a given worldview.

The striking result that arise from figure 2 is that the discount rate alone cannot

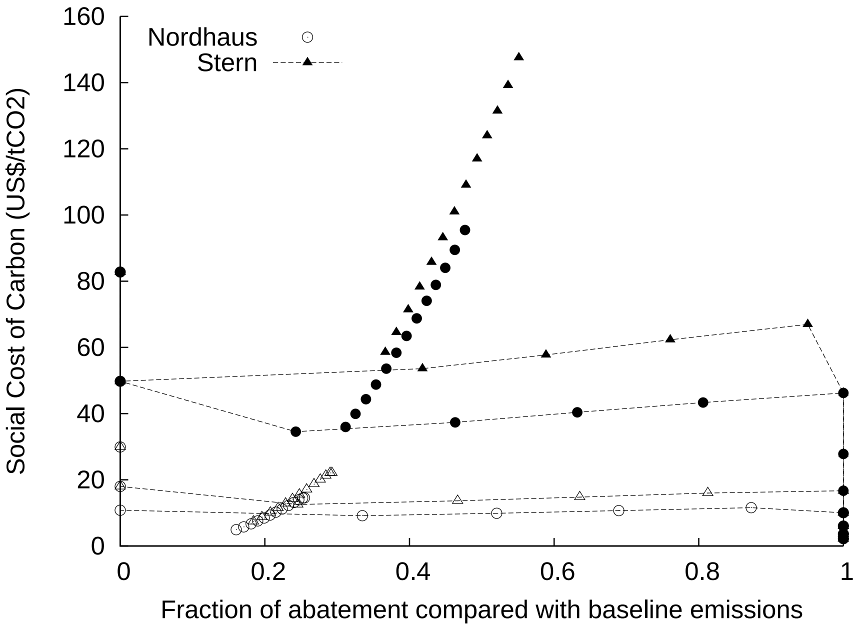

Figure 2: Mapping of the Stern-Nordhaus controversy structured around three drivers: the rate of pure time preference, technical progress on abatement costs, climate sensitivity. Empty circles at the bottom left of the figure stand for the time profile of the Nordhaus' optimal position from 2010 (the first circle) to 2130 (the last circle). Full triangles with lines and a slightly rising trend accross the figure stand in turn for the time profile of the Stern's optimal position. The six other time profiles account for a combination of Stern and Nordhaus' beliefs that compose other possible worldviews

be made responsible for the whole difference between Stern and Nordhaus viewpoints. Indeed a Nordhaus run with a Stern-like discount rate yields results with higher SCC (from 36 to $\$95 \Uparrow tCO_2$) and more abatement (from 31 to 48%) than the pure Nordhaus' one (respectively from 5 to $\$14,5 \Uparrow tCO_2$ and from 16% to 25.5%). In this case, the SCC even gets higher than Stern's results from 2060 on, while levels of abatement are quickly overtaken by Stern's level of abatement. Symetrically, the change of pure time preference in the Stern's run has a significant impact on results as the SCC lowers dramatically down to the range [$\$12 - 17 \Uparrow tCO_2$] during the decarbonization period (from 2050 to 2090) and abatement take-off is postponed to 2050. Yet, this change of pure time preference is not sufficient to recover Nordhaus' results.

Hence, other beliefs on abatement costs and climate sensitivity are clearly not negligible and must be considered to explain differences in results. Starting fom the Nordhaus' case, it is possible by construction to recover Stern's results by changing in turn Nordhaus' beliefs till recovering Stern's set of beliefs and *vice versa*. Running Nordhaus worldview with high climate sensitivity slightly increases results both in terms of SCC and abatement. The combination of low discount and high sensitivity leads to much higher results (full triangles with no lines) that end up exceeding Stern's results in terms of SCC from 2060 on while abatement increases slower and ends up at a lower level than in the Stern run. Then changing abatement costs makes it possible to recover Stern's time profile.

Note that for any given worldview, change in the rate of technological progress on abatement costs has a weaker impact on the SCC – which remains in the same order of magnitude – than on the timing of abatement. With low rate of technical progress, abatement levels never exceed 55% by 2130, while with high rate of technological progress abatement always ends up at 100% by 2100. In turn beliefs on the climate sensitivity has both an impact on abatement and the SCC.

To sum up, the mapping of results displayed in figure 2 indicates that the discount rate has a significant impact on results though it is not able to explain the whole gap of results. This is undoubtedly due to the interplay of other beliefs on climate sensitivity and abatement costs. It appears that beliefs on the rate of pure time preference and climate sensitivity have both an impact on the SCC and the level of abatement, while beliefs on the rate of decrease of abatement costs impact more the timing of abatement than the level of SCC. These results allow us to qualify the role played by the discount rate in the Stern/Nordhaus controversy. In next section we go beyond this graphical rationale and use a linear econometric model to measure the respective impact of beliefs on the key drivers of the SCC and mitigation efforts.

4 Disentangling the Relative Impact of Key Drivers of the Controversy: a Quantitative Analysis

A comprehensive sensitivity analysis on six key parameters of RESPONSE (taking five values each in ranges summarized in table 4) allows us to fill up a grid of results with 15625 scenarios. The grid is built so that each scenario appears on a single row where the values of both the SCC and abatement are given for 13 consecutive dates from 2010 to 2130. Each date appears twice in the columns of the grid. Hence, the wole set of scenarios can be considered as a single cross-section of scenarios and is suitable to a sound statistical analysis which will allow us to appraise quantitatively the respective impact of core parameters of RESPONSE on the SCC and abatement.

Table 4: Sensitivity analysis over 6 key parameters of RESPONSE

Growth rate	1% - 2.1%
Pure time preference	0.1% - 2.8%
Climate sensitivity	2 °C - 6 °C
Climate damage (curvature parameter)	0.00116 - 0.00452
Linear cost	0 - 229
Annual rate of technical progress	0.0025 - 0.05220

Here, we describe step by step the methodology. We first estimate regression equations for the two variables of interest, namely the SCC and abatement, with both ordinary least squares (OLS) and corrected heteroskedasticity generalized least-squares (GLS) estimators. Regression equations are composed of six explanatory variables, namely the rate of pure time preference, the rate of technical progress on abatement cost, climate sensitivity, the rate of long term growth, and the forms of both the climate damage and abatement cost functions.

The regression equations expressions at each date are thus given by:

$$SCC = constant + \beta_1 discount + \beta_2 costrate + \beta_3 lincost + \beta_4 sensibT + \beta_5 growth + \beta_6 sensibD,$$

and

$$Abat = constant + \alpha_1 discount + \alpha_2 costrate + \alpha_3 lincost + \alpha_4 sensibT + \alpha_5 growth + \alpha_6 sensibD,$$

with *discount* the rate of pure time preference, *costrate* the rate of technical progress, *sensibT* the climate sensitivity, *lincost* the linear part of the abatement cost function, *growth* the rate of economic growth, *sensibD* the form of climate damage, and α_i and β_i the regression coefficients.

The linear form of the models is satisfactory because the fits are very high for such large cross-sections. Figure 3 shows that R^2 computed at each date are comprised beteween $0,54$ and $0,91$ for both *Abat* and *SCC*. These rather unusually high levels of fit suggest a very good adjustment of the linear models. Note however that the values of the R^2 is not constant over time. In the case of abatment the R^2 is first quite low (0.54) in 2010, then culminates in 2070 at 0.91 and enventually slightly decreases down to 0.79 in 20130. Regarding the SCC, the profile of the R^2 is roughly inverse: it first decreases from 0.91 in 2010 (0.91) to 0.56 in 2050 and then stabilizes between 0.5 and 0.6.

Coefficient standard errors which were computed by the delta method (Greene, 2011) are very small. Then t-stats are highly significant as none of them yield results below several tens[7]. Still, residuals show some uncorrected heterogeneity that obliges us to interpret them cautiously. It seems that the residuals are affected by very large outliers which were not corrected in the present results and may be the principal source of heterogeneity in the models.

Second we derive from each estimated coefficient α_i and β_i at each date the corresponding mean point elasticity η_i and γ_i according to the following formula:

[7] t-stats are considered as significant as they yield results above 2

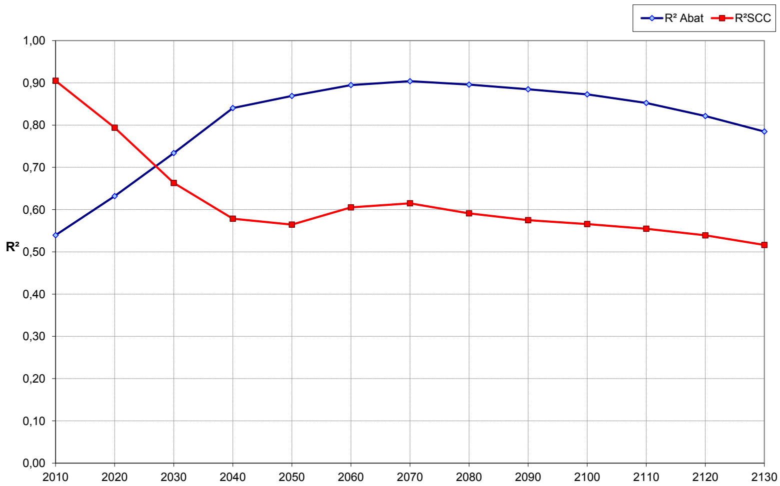

Figure 3: The chart represents the evolution over the period 2010 - 2030 of the R^2 computed for both *Abat* and SCC

$$\eta_i = \alpha_i \frac{\overline{x}}{\overline{SCC}},$$

and

$$\gamma_i = \beta_i \frac{\overline{x}}{\overline{Abat}}$$

where $\overline{x}$ is the means of the 6 explanatory variables (x_i), and $\overline{SCC}$ and $\overline{Abat}$ then means of the explained variables, i.e. the SCC and the abatement at each date.

These elasticities at each point in time allow us to appraise the evolution of the respective impact of the six explanatory variables on the SCC and the level of abatement. Elasticities results should be read that way: an elasticity of -0.27 of the parameter $discount$ in 2040 for instance means that a one percent increase of the rate of pure time preference in 2040 implies a -0.27 percent decrease in the SCC in 2040. All computations were performed in the GRETL econometrics software (Cottrell and Lucchetti, 2011).

For all of these results, given that the GLS estimator is consistent, standard errors of the elasticities are too small to be reported. Hence our results are highly significant at the usual levels and we only plot the elasticities themselves.

Time profiles of the elasticities over the period 2010 - 2130 are plotted in figures 4 and 5.

Restricting[8] the analysis to the three key drivers of the Stern/Nordhaus controversy (namely pure time preference, technical progress and climate sensitivity), we note that

[8] As the same analysis performed on a reduced statistical model only composed of the three variables that distinguish Stern and Nordhaus yielded the same pattern of elasticities profiles and did not alter either the sign nor the ranking of the respective impact of variables on results we only present the complete statistical model

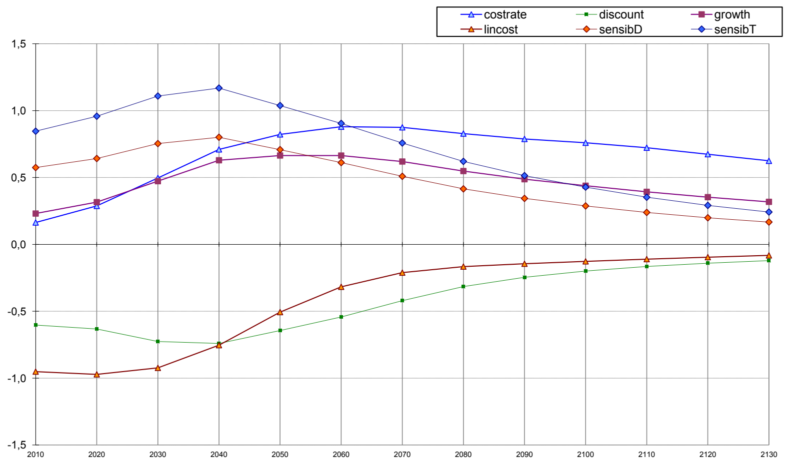

Figure 4: The chart represents the evolution over the period 2010 - 2030 of mean point elasticities of abatement

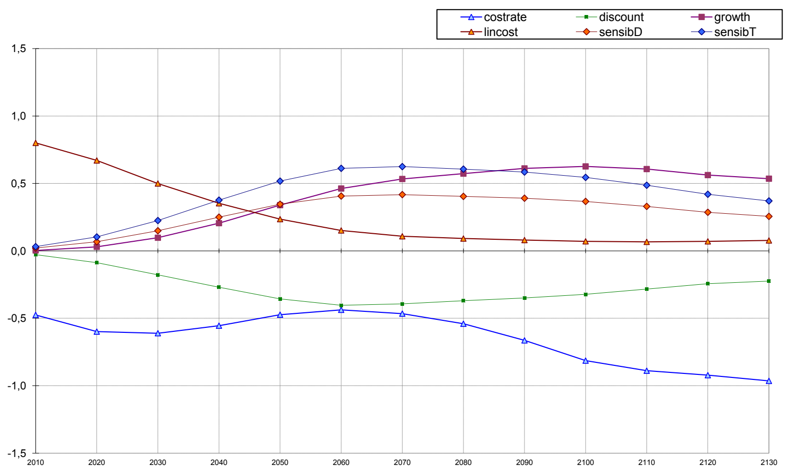

Figure 5: The chart represents the evolution over the period 2010 - 2030 of mean point elasticities of the SCC

technical progress has opposite impacts on the SCC and abatement, driving up abatement and driving down the SCC while pure time preference and climate sensitivity have respectivily negative and positive impacts on both the abatement and the SCC.

Over the period 2010 - 2130 the three variables have a growing impact on abatement that peak in 2040 for pure time preference and climate sensitivity and in 2070 for technical progress. From 2060 the impact of technical progress becomes preponderant as the impacts of both climate sensitivity and pure time preference decrease steadily till 2130. Note that from 2050 on the impacts of both technical progress and climate sensitivity outweigh the impact of pure time preference.

Regarding the impacts on the SCC, a different pattern comes up in figure 5. While the impacts of climate sensitivity and pure time preference display a similar trend as in the abatement case, with a peak in respectively 2070 and 2060, technical progress has a growing impact over time which ends up close to an elasticity of -1.

In both cases, the striking result is that the impact of pure time preference is most of the time weaker than the impacts of technological progress and climate sensitivity and tends to decrease with time. Those results clearly makes the case for qualifying the actual role of the discounting issue in the Stern/Nordhaus controversy.

Eventually, extending the analysis to other core parameters of RESPONSE, it turns out that the rate of long term economic growth and the form of the climate damage function have major impacts of the same order of magnitude as climate sensitivity and pure time preference. Note that the elasticity of economic growth even becomes the second more important one in the long run. Elaticities of *lincost* (the linear part of the abatement cost function) displays a different pattern as it decreases steadily over time and tends to zero in both cases thanks to technological progress.

This extended analysis brings an additional argument to qualify the impact of the discounting clash on differences in modelling results and climate policy recommendations.

5 Toward a Transparent Modelling Framework to Negotiate Climate Policies

Disentangling the Stern/Nordaus controversy requires to go beyond the discounting clash that has been heavily commented. RESPONSE makes it possible to map the relative impact of other key drivers of the controversy such as technical progress and climate sensitivity. Then a statistical analysis clearly shows that the rate of pure time preference has a significant impact on results though less important over time than other beliefs on technical progress, climate sensitivity, the rate of long term economic growth and climate damages.

Hence, if a Social Cost of Carbon were to be negotiated among countries, the take-away message of this analysis for decision-makers would be that they should not focus too much on the setting of the discount rate which is only one driver of the results. Instead, a more comprehensive analysis of each component of the worldviews expressed in the debate would better reveal the stumbling blocks of negotiations or conversely indicate the possible ways toward an agreement.

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