Intergenerational equity under catastrophic climate change

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Introduction

- Since Cline (1992) and Nordhaus (1994), climate change has been modelled as an issue of intertemporal consumption trade-off:
    - the costs of climate change mitigation lower consumption today, but increase consumption in the future as some damages are avoided
    - this assumes that climate change occurs at a slow pace and has reversible impacts
- However, possibility of tipping points:
    - abrupt and irreversible changes (Lenton et al. 2008), (Scheffer et al., 2001), e.g. shutoff of the Atlantic thermohaline circulation
    - possibly bringing catastrophic outcomes
    - including indirect impacts, e.g. increased migration and conflicts (Reuveny, 2007), (Hsiang et al., 2013)

Literature review

- In the economics literature, catastrophic outcomes are modelled as a reduction of society's level of consumption or welfare:
    - irreversible decline to zero (Cropper, 1976), (Clarke and Reed, 1994) or partially reversible decline (Tsur and Zemel, 1996)
- A drop of social welfare to zero can be interpreted as human extinction
    - The trade-off is then between present consumption and the existence of future generations (Weitzman, 2009)
- This trade-off has been little studied, with the exception of Bommier et al. (2015) and Martin and Pindyck (2017)
- It raises the issue of evaluating policies with varying population size (Broome, 2012), largely ignored in the literature
- This paper aims at filling this gap by examining the issue of population ethics, i.e. the collective attitudes towards population size in the context of climate change

In this paper

- This paper aims at studying climate policy when facing an endogenous extinction risk
- We explicitly model ethical views and study how the most preferred climate policy depends on: inequality aversion and population ethics.
- We include an endogenous risk of extinction due to climate change in an integrated assessment model
- We depart from the standard optimization framework: instead we consider various climate policies that are ordered according to their performance in terms of welfare

- We find that introducing even a very small endogenous risk pushes for stringent climate policy in most cases
- We highlight a non-monotonic role of inequality aversion, while a preference for larger populations calls for stringent climate policy

Outline

Analytical framework and results

The numerical model

Numerical results

Analytical framework

- a sequence of non-overlapping generations indexed by t
- exogenous population size (conditional on existence): n_t
- total population up to generation t:

$$N_t = \sum_{\tau=0}^{t} n_\tau$$

- a policy (or scenario) will result in each period in aggregate and per capita consumption levels (conditional on existence):

$$C_t = n_t \cdot c_t$$

Analytical framework

Definition 1 (Variable population utilitarian social welfare functions)
For a finite horizon T, a social welfare function is a *variable population utilitarian social welfare function* if there exist real numbers $\beta \in [0,1]$, $\bar{c} \in \mathbb{R}_{++}$ and $\eta \in \mathbb{R}_{+}$ such that:

$$U(c) = N_T^{\beta-1} \left\{ \sum_{\tau=0}^{T} n_\tau \left[\frac{c_\tau^{1-\eta}}{1-\eta} - \frac{\bar{c}^{1-\eta}}{1-\eta} \right] \right\} \tag{1}$$

c_τ	consumption per capita at date τ
N_t	total population up to date t
n_τ	size of generation τ
$\overline{c}$	threshold level of consumption per capita
η	inequality aversion parameter
β	population ethics parameter

Variable population utilitarian social welfare function

$$U(c) = N_T^{\beta - 1} \left\{ \sum_{\tau=0}^{T} n_\tau \left[\frac{c_\tau^{1-\eta}}{1-\eta} - \frac{\bar{c}^{1-\eta}}{1-\eta} \right] \right\}$$

- η is the inequality aversion. High η means:
  - we are willing to sacrifice more to equalize consumption across individuals
- β determines the value of larger populations
  - *total utilitarianism* ($\beta = 1$) vs. *average utilitarianism* ($\beta = 0$)
  - values of β between 0 and 1 span cases between total and average views ("number-dampened utilitarianism") (Ng, 1989; Boucekkine et al., 2014).
- $\bar{c}$ is the consumption threshold parameter
  - when $\beta = 1$, the criterion favors adding individuals to the population only if their consumption is above $\bar{c}$: critical-level utilitarianism (Blackorby et al., 2005)
  - when $\beta \neq 1$, the critical level is endogenous but depends on $\bar{c}$

Expected variable population utilitarian social welfare function

- With a risk of extinction, aggregate welfare W depends on both the streams of consumption per capita c and hazard rate p
- W is the expected value of a variable population utilitarian SWF
- $P_t = p_t \prod_{\tau=0}^{t-1}(1-p_\tau)$ is the probability that there exists exactly t generations

$$W(c,p) = \mathbb{E}\left[U(c)\right] = \sum_{T=0}^{\infty} P_T \left(N_T^{\beta-1} \left\{ \sum_{\tau=0}^{T} n_\tau \left[\frac{c_\tau^{1-\eta}}{1-\eta} - \frac{\bar{c}^{1-\eta}}{1-\eta} \right] \right\} \right) \tag{2}$$

W	welfare
p_t	hazard rate
P_t	planning horizon probability
c_τ	consumption per capita at date τ
N_t	total population up to date t
n_τ	size of generation τ
$\bar{c}$	threshold level of consumption per capita
η	inequality aversion parameter
β	population ethics parameter

Expected variable population utilitarian social welfare functions

$$
\begin{aligned}
W(c,p) = \mathbb{E}\left[U(c)\right] \quad &= \quad \sum_{T=0}^{\infty} P_T \left(N_T^{\beta-1} \left\{ \sum_{\tau=0}^{T} n_\tau \left[\frac{c_\tau^{1-\eta}}{1-\eta} - \frac{\bar{c}^{1-\eta}}{1-\eta} \right] \right\} \right) \\
&= \quad \sum_{\tau=0}^{\infty} \left(\underbrace{\sum_{t=\tau}^{\infty} P_t N_t^{\beta-1}}_{\theta_\tau} \right) n_\tau \left[\frac{c_\tau^{1-\eta}}{1-\eta} - \frac{\bar{c}^{1-\eta}}{1-\eta} \right]. \qquad (3)
\end{aligned}
$$

- θ_τ is like a discount factor on the wellbeing of generation τ
- it arises from the uncertainty about the planning horizon
- there is no 'pure' discounting of the utility of future generations: generation are treated generations in a fair (i.e. symmetric) way, cf. (Ramsey, 1928) and (Stern, 2007)
- instead, discounting depends on the risk of extinction and on attitudes towards population size (through β)

Evaluating policy change: the marginal case

- Consider a marginal policy that:
  - reduces consumption in period 0 by a small amount dc_0
  - increases future consumption (dc_t: reduction of climate damages)
  - reduces the hazard rate ($-dp_t$)
- The total welfare gain is:

$$\begin{aligned} dW &= -dc_0 \frac{\partial W}{\partial c_0} + \sum_{T=1}^{\infty} dc_T \frac{\partial W}{\partial c_T} - \sum_{T=1}^{\infty} dp_T \frac{\partial W}{\partial p_T} \\ &= dc_0 \frac{\partial W}{\partial c_0} \left(-1 + \sum_{T=1}^{\infty} \frac{1}{(1+\rho_T)^T} \left(\frac{dc_T}{dc_0} + \xi_T \frac{dp_T}{dc_0} \right) \right) \end{aligned} \tag{4}$$

with ρ_T the social discount rate, ξ_T the social value of catastrophic risk reduction

- This disentangles the impacts on consumption and on the risk profile

Social discount rate

Definition 2: Social discount rate

The social discount rate from generation 0 to generation t is:

$$\rho_t = \left(\frac{\frac{\partial W}{\partial C_0}}{\frac{\partial W}{\partial C_t}} \right)^{\frac{1}{t}} - 1 = \left(\frac{c_t}{c_0} \right)^{\frac{\eta}{t}} \left(\frac{\sum_{T=0}^{\infty} P_T N_T^{\beta-1}}{\sum_{T=t}^{\infty} P_T N_T^{\beta-1}} \right)^{\frac{1}{t}} - 1. \qquad (5)$$

- increasing η (when $c_t \geq c_0$) increases the discounting of future benefits and may thus reduce the value of the policy
- increasing β decreases the social discount rate, because future generations become more valuable as they increase total population size (see proof in paper)
- let us define δ_t, the endogenous time preference rate, such that: $(1+\delta_t)^t = \frac{\theta_0}{\theta_t}$ with $\theta_t = \sum_{T=t}^{\infty} P_T N_T^{\beta-1}$
- we obtain the Ramsey formula in discrete time:

$$1 + \rho_t = (1+\delta_t)(1+g_t)^\eta$$

- hence introducing a risk of extinction is equivalent to introducing an endogenous pure time preference rate

Social value of catastrophic risk reduction

Definition 3: Social value of catastrophic risk reduction

The social value of catastrophic risk reduction in period t is:

$$\xi_t = -\frac{\frac{\partial W}{\partial p_t}}{\frac{\partial W}{\partial C_t}} = -\frac{\sum_{T=0}^{\infty} \frac{\partial P_T}{\partial p_t} \left(N_T^{\beta} A W_T(C) \right)}{(c_t)^{-\eta} \sum_{T=t}^{\infty} P_T N_T^{\beta - 1}} \tag{6}$$

- as policy may affect the probability of catastrophic events, we need a tool to attribute a monetary value to risk reduction
- ξ_t describes how much a generation wants to pay to avoid extinction before the next period
- the concept was first introduced in Bommier et al. (2015), relates to 'the value of statistical civilization' (Weitzman, 2009)
- resembles the value of a statistical life (VSL) as it measures a risk-consumption trade-off.
- ξ_t has more to do with the willingness to add people to a population than extending the life of existing individuals.

Social value of catastrophic risk reduction

- $AW_T(C)$ is the average welfare when there are exactly T generations, with $U(C) = N_T^{\beta} \cdot AW_T(C)$:

$$AW_T(C) = \left\{ \sum_{\tau=0}^{T} \frac{n_\tau}{N_T} \left[\frac{\left(c_\tau\right)^{1-\eta}}{1-\eta} - \frac{\bar{c}^{1-\eta}}{1-\eta} \right] \right\} \tag{7}$$

- We then have:

$$\xi_t = \frac{\sum_{T=t}^{\infty} P_T^{|t} \left(N_T^{\beta} AW_T(C) \right) - N_t^{\beta} AW_t(C)}{(1-p_t)(c_t)^{-\eta} \sum_{T=t}^{\infty} P_T^{|t} N_T^{\beta-1}} \tag{8}$$

- numerator: expected gain from living longer than for just t generations (conditional on the t first generations existing)
- denominator: chance of survival at t; marginal social value of consumption at t; another conditional expectation
- overall effects of η and β on ξ_t is unclear

Evaluating policy change: the marginal case

$$dW = dc_0 \frac{\partial W}{\partial c_0} \left(-1 + \sum_{T=1}^{\infty} \frac{1}{(1+\rho_T)^T} \left(\frac{dc_T}{dc_0} + \xi_T \frac{dp_T}{dc_0} \right) \right) \tag{9}$$

with ρ_T the social discount rate, ξ_T the social value of catastrophic risk reduction

- the effect of ethical parameters on ξ_T is unclear
- hence the effect of ethical parameters on dW is unclear
- the formula only holds for marginal policies, which are not those we are interested in

Non-marginal policies: decomposing welfare change

- Consider two policies i and j:
  - policy j leads to lower emissions than policy i
  - $p_{i,t} \geq p_{j,t}$: less mitigation in i leads to a higher hazard rate
  - no damages: c_i and c_j are increasing consumption streams
- The preferred policy depends on the sign of $\Delta W = W(c_j, p_j) - W(c_i, p_i)$

$$\begin{aligned} \Delta W &= (W(c_j, p_j) - W(c_j, p_i)) - (W(c_i, p_i) - W(c_j, p_i)) \\ &= \Delta_p W - \Delta_c W \end{aligned} \tag{10}$$

- $\Delta_p W$ is the part explained by the variation of *hazard rate*
- $\Delta_c W$ is the part explained by the variation of *consumption*
- We show that without climate damages, both terms are positive, increasing with β, decreasing with η (cf. below)

Non-marginal policies: evolution of $\Delta_c W$ with η and β

We note:

$$AW_T(c) = \sum_{\tau=0}^{T} \frac{n_\tau}{N_T} \left[\frac{c_\tau^{1-\eta}}{1-\eta} - \frac{\bar{c}^{1-\eta}}{1-\eta} \right]$$

$$\begin{aligned} \Delta_c W &= W(c_i, p_i) - W(c_j, p_i) \\ &= \sum_t N_t^\beta P_t \left(AW_t^i(c) - AW_t^j(c) \right) \end{aligned} \tag{11}$$

- we show that when $c_\tau^i \geq c_\tau^j$, $\frac{\left(c_\tau^i\right)^{1-\eta}}{1-\eta} - \frac{\left(c_\tau^j\right)^{1-\eta}}{1-\eta}$ is decreasing in η, hence:
- $\Delta_c W$ decreases in η, i.e. a large η lowers the welfare gained due to higher consumption streams
- $\Delta_c W$ increases in β

Non-marginal policies: evolution of $\Delta_p W$ with η and β

$$AW_T(c) = \sum_{\tau=0}^{T} \frac{n_\tau}{N_T}(u(c) - u(\bar{c}))$$

$$\begin{aligned} \Delta_p W &= W(c_j, p_j) - W(c_j, p_i) \\ &= \sum_{t=0}^{\infty} N_t^\beta \cdot (P_t^j - P_t^i) \cdot AW_t(c^j) \end{aligned} \tag{12}$$

- $\Delta_p W$ decreases with η: a large η reduces the value of postponing extinction (cf. proof in paper), intuition:
    - as η increases, the concavity of u increases, bringing $u(c)$ closer to $u(\overline{c})$
    - the welfare gain of increasing c above $\overline{c}$ is thus lower at high η
    - therefore, the added welfare due to a larger population (i.e. the welfare gained due to a lower risk profile) is lower
- $\Delta_p W$ increases with β

Proposition

$$\Delta W = \Delta_p W - \Delta_c W$$

- The preferred policy depends on the relative effect of η and β on the welfare lost due to a lower consumption stream and the welfare gained due to a lower hazard rate
- $\Delta_p W$ and $\Delta_c W$ are both positive, decreasing with η, increasing with β
- a large η reduces both the welfare lost due to a lower consumption stream, and the welfare gained due to a lower hazard rate (i.e. the value of postponing extinction)
- a large β increases both the welfare lost due to a lower consumption stream, and the welfare gained as the size of the cumulative population increases due to a lower hazard rate
- hence we cannot predict the sign or evolution of ΔW with β and η
- this calls for a numerical analysis

The numerical model

- The Response model (Dumas et al., 2012) details
    - Ramsey-like growth model with capital accumulation
    - Simple climate model, describing the evolution of global temperature and radiative forcing
- The recursive version (python)
    - abatement and saving rate are imposed, $s = 25.8\%$ following (Golosov et al., 2014) and (Dennig et al., 2015)
    - climate policies are ordered according to welfare

The catastrophic risk

- Risk of extinction: hazard rate function of temperature increase
- Obviously, we cannot calibrate the global catastrophic risk on data
- We assume that the catastrophe is irreversible and is akin to truncating the planning horizon, following Cropper (1976)

$$p(T) = \begin{cases} p_0, & \text{if } T \leq T_0 \\ p_0 + b \cdot (T - T_0), & \text{if } T_0 \leq T \leq T_0 + \frac{1-p_0}{b} \\ 1, & \text{if } T \geq T_0 + \frac{1-p_0}{b}; \end{cases} \tag{13}$$

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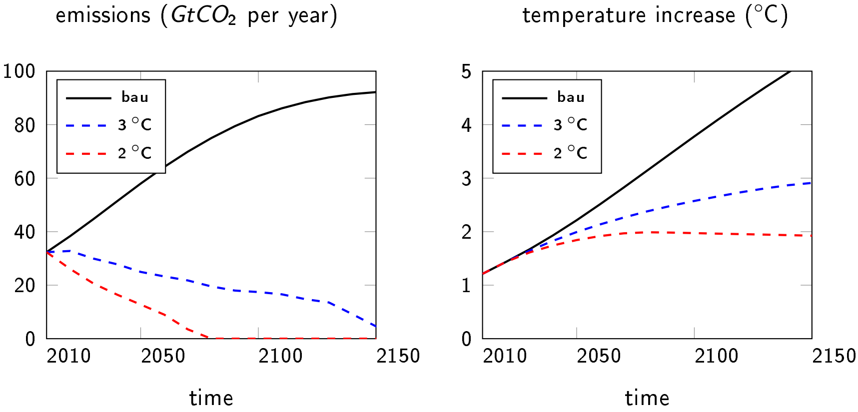
p	hazard rate (per annum)
p_0	minimum hazard rate (set at 1e-3 per annum)
T	temperature increase compared to pre-industrial levels (°C)
T_0	temperature increase above which the hazard rate starts rising (set at 1 °C)
b	marginal hazard rate (per °C above T_0)

Contributions

- ΔW can either be explained by a difference in c, p, or both
- c and p streams vary simultaneously: we cannot easily identify the cause of variation
- solution: change one stream at a time
- signs of $\Delta W \cdot \Delta_c W$ and $\Delta W \cdot \Delta_p W$:
  - if + : variation attributed to the associated variable
  - if - : that variable counteracts

product of welfare differences		*diagnostic*
$\Delta W \cdot \Delta_c W$	$\Delta W \cdot \Delta_p W$	
+	+	Δc_t and Δp_t cause ΔW
+	-	Δc_t causes ΔW, Δp_t counteracts
-	+	Δp_t causes ΔW, Δc_t counteracts

Climate policies

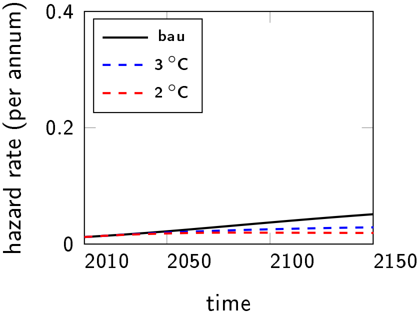


emissions ($GtCO_2$ per year)

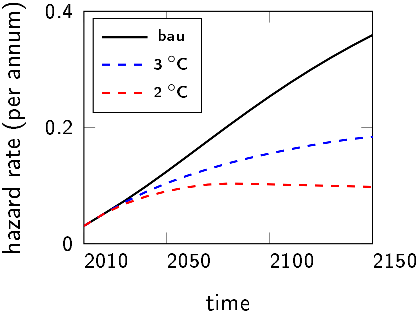
temperature increase (°C)

Parameters

parameter	*description*	*value*
η	inequality aversion parameter	between 0.5 and 5.0
β	population parameter	between 0 and 1
b	marginal hazard rate	between 0 and 10^{-2} per °C
$\bar{c}$	threshold parameters	2.7 USD per day per capita



$b = 10^{-4}$ per °C



$b = 10^{-2}$ per °C

Hazard rate and probability of survival

- $p_0 = 10^{-3}$ per annum: with a purely exogenous risk of extinction, the probability of survival after a hundred years is 90%

- assuming constant T at 2 °C (i.e. 1 °C above the threshold), the probability of survival after a hundred years would be:
    - 89% for $b = 10^{-4}$ per °C
    - 82% for $b = 10^{-3}$ per °C
    - 30% for $b = 10^{-2}$ per °C

Effects at play

- intertemporal consumption trade-off
  - as future generations are assumed to be richer, a high η gives preference to present consumption. This could lead to favour no abatement in order to preserve the consumption of the present, poorer generation.
- trade-off between consumption today and the existence of future generations
  - climate policy can delay extinction due to climate change, short-term abatement can be favoured, translating into lower consumption of the present generation, as abatement is costly.
- the risk of extinction discounts future welfare
  - this has an impact on the intertemporal consumption trade-off as the contribution of the welfare of future generations can become negligible with a high hazard rate.

Numerical results

1. The role of the risk of extinction
2. The role of population ethics
3. The role of inequality aversion
4. The role of damages

1. The role of the risk of extinction ($\beta = 1$, $\eta = 2$)

b (per $^\circ C$)						
0	10^{-7}	10^{-6}	10^{-5}	10^{-4}	10^{-3}	10^{-2}
bau	3°C	3°C	3°C	3°C	3°C	3°C

□ Δc_t causes ΔW, Δp_t plays no role

▨ Δp_t causes ΔW, Δc_t counteracts

- *bau* is preferred for a purely exogenous hazard rate (equivalent to pure time discounting): the social objective can be improved by maximising early consumption, when extinction has not occured yet
- when $b \neq 0$, the 3 °C policy is preferred: climate action may avoid extinction
- not shown here: very high marginal hazard rate ($b \geq 0.5$ per °C) favours the *bau* (doomed situation)

1. The role of the risk of extinction ($\beta = 1$, $\eta = 2$)

b (per $^\circ C$)

0	10^{-7}	10^{-6}	10^{-5}	10^{-4}	10^{-3}	10^{-2}
□ bau	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C

□ Δc_t causes ΔW, Δp_t plays no role

▨ Δp_t causes ΔW, Δc_t counteracts

- 3 °C is preferred due to the variation in hazard rate, while consumption counteracts
- *bau* is preferred due to the variation in consumption, while the hazard rate counteracts or plays no role
  - without climate damages, emissions reductions reduce both the hazard rate and consumption

1. The role of the risk of extinction ($\beta = 1$, $\eta = 2$)

b (per $^\circ C$)

0	10^{-7}	10^{-6}	10^{-5}	10^{-4}	10^{-3}	10^{-2}
□ 3°C	□ 3°C	▨ 2°C	▨ 2°C	▨ 2°C	▨ 2°C	▨ 2°C

□ Δc_t causes ΔW, Δp_t plays no role

▨ Δp_t causes ΔW, Δc_t counteracts

- even a very small endogenous risk of extinction ($b \geq 10^{-6}$) leads to adopt a more ambitious climate policy (the 2 °C scenario)

2. The role of population ethics ($\eta = 2$)

β											b (per $^\circ C$)
0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	
3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	$[10^{-5}; 10^{-2}]$
bau	3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	10^{-6}
bau	bau	bau	3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	10^{-7}
bau	bau	bau	bau	bau	bau	bau	bau	bau	bau	bau	0

□ Δc_t causes ΔW, Δp_t counteracts (or plays no role)

■ Δp_t causes ΔW, Δc_t counteracts (or plays no role)

- a large weight on population size favours the 3 °C scenario: intuitive result, as cumulative population is larger if climate change is delayed
- β plays no role for $b \geq 10^{-5}$

2. The role of population ethics ($\eta = 2$)

β											b (per $^{\circ}C$)
0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	
2°C	2°C	2°C	2°C	2°C	2°C	2°C	2°C	2°C	2°C	2°C	$[10^{-4}; 10^{-2}]$
3°C	2°C	2°C	2°C	2°C	2°C	2°C	2°C	2°C	2°C	2°C	10^{-5}
3°C	3°C	3°C	3°C	2°C	2°C	2°C	2°C	2°C	2°C	2°C	10^{-6}
3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	10^{-7}
3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	0

□ Δc_t causes ΔW, Δp_t counteracts (or plays no role)

▨ Δp_t causes ΔW, Δc_t counteracts (or plays no role)

- similar results when comparing 3 °C and 2 °C

3. The role of inequality aversion ($\beta = 0$)

η										b (per $^\circ C$)
0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	
3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	$[4.10^{-6}; 10^{-2}]$
3°C	3°C	3°C	3°C	bau	bau	bau	bau	bau	bau	3.10^{-6}
3°C	3°C	3°C	bau	bau	bau	bau	bau	bau	bau	2.10^{-6}
3°C	3°C	bau	bau	bau	bau	bau	bau	bau	bau	$[10^{-7}; 10^{-6}]$
bau	bau	bau	bau	bau	bau	bau	bau	bau	bau	0

░ Δc_t causes ΔW, Δp_t counteracts (or plays no role)

▒ Δp_t causes ΔW, Δc_t counteracts (or plays no role)

- a low η favours the most ambitious policy (standard result)

3. The role of inequality aversion ($\beta = 0$)

η										b (per $^\circ C$)
0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	
3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	$[4.10^{-6}; 10^{-2}]$
3°C	3°C	3°C	3°C	bau	bau	bau	bau	bau	bau	3.10^{-6}
3°C	3°C	3°C	bau	bau	bau	bau	bau	bau	bau	2.10^{-6}
3°C	3°C	bau	bau	bau	bau	bau	bau	bau	bau	$[10^{-7}; 10^{-6}]$
bau	bau	bau	bau	bau	bau	bau	bau	bau	bau	0

░ Δc_t causes ΔW, Δp_t counteracts (or plays no role)

▒ Δp_t causes ΔW, Δc_t counteracts (or plays no role)

- for $b \geq 4.10^{-6}$ per °C, η plays no role (3 °C is always preferred).

3. The role of inequality aversion ($\beta = 0$)

η										b (per $^\circ C$)
0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	
3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	$[4.10^{-6}; 10^{-2}]$
3°C	3°C	3°C	3°C	bau	bau	bau	bau	bau	bau	3.10^{-6}
3°C	3°C	3°C	bau	bau	bau	bau	bau	bau	bau	2.10^{-6}
3°C	3°C	bau	bau	bau	bau	bau	bau	bau	bau	$[10^{-7}; 10^{-6}]$
bau	bau	bau	bau	bau	bau	bau	bau	bau	bau	0

▢ Δc_t causes ΔW, Δp_t counteracts (or plays no role)

▨ Δp_t causes ΔW, Δc_t counteracts (or plays no role)

- as b decreases, the minimum η that justifies the least ambitious policy is reduced
- richer generations are added, which enhances inequalities between generations
- similar results when comparing 3 °C and 2 °C

3. The role of inequality aversion ($\beta = 0.1$)

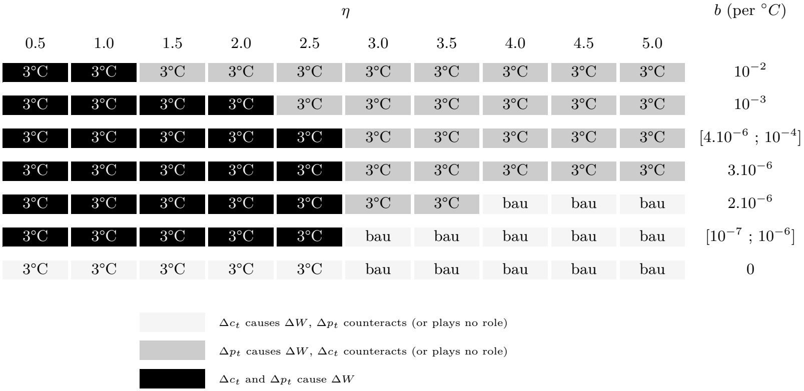
η										b (per $^\circ C$)
0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	
3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	$[10^{-6}; 10^{-2}]$
3°C	3°C	bau	bau	bau	3°C	3°C	3°C	3°C	3°C	10^{-7}
bau	bau	bau	bau	bau	bau	bau	bau	bau	bau	0

□ Δc_t causes ΔW, Δp_t counteracts (or plays no role)

▨ Δp_t causes ΔW, Δc_t counteracts (or plays no role)

- increasing η still favours the least ambitious climate policy for low values of η (≤ 1.5)
- however, the effect is reversed for higher values of η (≥ 2.5)
- as shown in the analytical results: increasing η reduces both the welfare lost due to a lower consumption stream, and the welfare gained due to a lower hazard rate (i.e. the value of postponing extinction)

4. The role of damages ($\beta = 0$)



η										b (per $^\circ C$)
0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	
3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	10^{-2}
3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	10^{-3}
3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	$[4.10^{-6}\ ;\ 10^{-4}]$
3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	3°C	3.10^{-6}
3°C	3°C	3°C	3°C	3°C	3°C	3°C	bau	bau	bau	2.10^{-6}
3°C	3°C	3°C	3°C	3°C	bau	bau	bau	bau	bau	$[10^{-7}\ ;\ 10^{-6}]$
3°C	3°C	3°C	3°C	3°C	bau	bau	bau	bau	bau	0

□ Δc_t causes ΔW, Δp_t counteracts (or plays no role)

▨ Δp_t causes ΔW, Δc_t counteracts (or plays no role)

■ Δc_t and Δp_t cause ΔW

- with climate damages, the 3 °C policy is preferred due to both risk and consumption for low η (≤ 2.5)
- without climate damages, the 3 °C policy was preferred due to the difference in hazard rate alone, while consumption counteracted

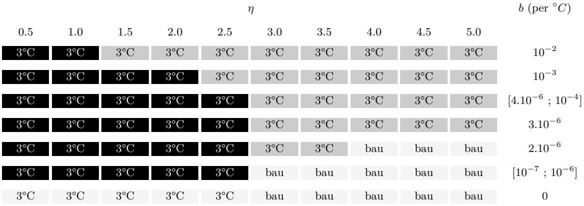
4. The role of damages ($\beta = 0$)

η										b (per $^\circ C$)
0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	
■ 3°C	■ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	10^{-2}
■ 3°C	■ 3°C	■ 3°C	■ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	10^{-3}
■ 3°C	■ 3°C	■ 3°C	■ 3°C	■ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	$[4.10^{-6} ; 10^{-4}]$
■ 3°C	■ 3°C	■ 3°C	■ 3°C	■ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	3.10^{-6}
■ 3°C	■ 3°C	■ 3°C	■ 3°C	■ 3°C	▨ 3°C	▨ 3°C	□ bau	□ bau	□ bau	2.10^{-6}
■ 3°C	■ 3°C	■ 3°C	■ 3°C	■ 3°C	□ bau	□ bau	□ bau	□ bau	□ bau	$[10^{-7} ; 10^{-6}]$
□ 3°C	□ 3°C	□ 3°C	□ 3°C	□ 3°C	□ bau	□ bau	□ bau	□ bau	□ bau	0

□	Δc_t causes ΔW, Δp_t counteracts (or plays no role)
▨	Δp_t causes ΔW, Δc_t counteracts (or plays no role)
■	Δc_t and Δp_t cause ΔW

- for a given η (e.g. $\eta = 2.5$) and increasing b (e.g. 10^{-4} to 10^{-3}): consumption no longer causes ΔW, as a higher b discounts the impact of damages on future consumption, i.e. the benefits in terms of long term consumption of the 3 °C scenario have less weight in total welfare as future generations are less likely to exist

4. The role of damages ($\beta = 0$)

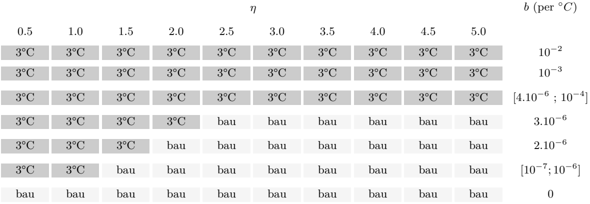


					η					b (per $^\circ C$)
0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	
■ 3°C	■ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	10^{-2}
■ 3°C	■ 3°C	■ 3°C	■ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	10^{-3}
■ 3°C	■ 3°C	■ 3°C	■ 3°C	■ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	$[4.10^{-6}\ ;\ 10^{-4}]$
■ 3°C	■ 3°C	■ 3°C	■ 3°C	■ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	3.10^{-6}
■ 3°C	■ 3°C	■ 3°C	■ 3°C	■ 3°C	▨ 3°C	▨ 3°C	□ bau	□ bau	□ bau	2.10^{-6}
■ 3°C	■ 3°C	■ 3°C	■ 3°C	■ 3°C	□ bau	□ bau	□ bau	□ bau	□ bau	$[10^{-7}\ ;\ 10^{-6}]$
□ 3°C	□ 3°C	□ 3°C	□ 3°C	□ 3°C	□ bau	□ bau	□ bau	□ bau	□ bau	0

□ Δc_t causes ΔW, Δp_t counteracts (or plays no role)

▨ Δp_t causes ΔW, Δc_t counteracts (or plays no role)

■ Δc_t and Δp_t cause ΔW



					η					b (per $^\circ C$)
0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	
▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	10^{-2}
▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	10^{-3}
▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	$[4.10^{-6}\ ;\ 10^{-4}]$
▨ 3°C	▨ 3°C	▨ 3°C	▨ 3°C	□ bau	□ bau	□ bau	□ bau	□ bau	□ bau	3.10^{-6}
▨ 3°C	▨ 3°C	▨ 3°C	□ bau	□ bau	□ bau	□ bau	□ bau	□ bau	□ bau	2.10^{-6}
▨ 3°C	▨ 3°C	□ bau	□ bau	□ bau	□ bau	□ bau	□ bau	□ bau	□ bau	$[10^{-7}; 10^{-6}]$
□ bau	□ bau	□ bau	□ bau	□ bau	□ bau	□ bau	□ bau	□ bau	□ bau	0

- adding climate damages mostly keeps the preferred policy unchanged (no change at all for $b \geq 4.10^{-6}$ per °C)

Conclusion: analytical results

- Discounting depends on the hazard rate and on the attitudes towards population size (parameter β)
- We show that we cannot predict the impact of changes in η and β on the preferred policy (case without damages)
    - increasing η reduces the welfare lost due to a lower consumption stream, it also reduces the value of postponing extinction (i.e the welfare gained as the size of the cumulative population increases due to a lower hazard rate)
    - increasing β increases the welfare lost due to a lower consumption stream, it also increases the value of postponing extinction

Conclusion: numerical results

- Even a very small endogenous risk of extinction ($b \geq 10^{-6}$) leads to adopt a more ambitious climate policy (the 2 °C scenario), almost irrespective of the value of the ethical parameters
- A large population ethics parameter (β) always favours the most ambitious policy
  - a large β gives as a large weight to the welfare of future generations
- Inequality aversion (η) has a non-monotonic impact on the preferred policy
- A small η always favours the most ambitious policy
  - consistent with intuition, as future generation are assumed to be richer
- However, we find cases where increasing η favours the most ambitious policy
  - this is due to the relative effect of inequality aversion on the risk and consumption components of the welfare difference
- Accounting for climate damages (in addition to the risk of extinction) leaves the order of policies unchanged (except for very low values of b)

Further work

- This paper is part of a broader project on the effects of climate change on population
- We would like to consider less extreme population impacts:
  - Endogenous risk may constantly reduce population size by some factor
  - Endogenous risk may affect life expectancy and mortality risk rather than population size
- We would like to consider population impacts that may be different in different parts of the world. This would raise new equity/fairness issues.
- We have explored a specific class of social welfare functions. We plan to explore other possibilities to disentangle inequality aversion and risk aversion

Thank you!

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