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**The welfare implications of climate change-related
mortality: Inequality and population ethics**

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The welfare implications of climate change-related mortality: Inequality and population ethics

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Abstract

Climate change-related mortality may strongly affect human well-being. By reducing life expectancy, it reduces the well-being of some individuals. This may exacerbate existing inequalities: ex-ante inequality among people in different groups or regions of the world; ex-post inequality in experienced well-being by people in the same generation. But mortality may also reduce total population size by preventing some individuals from having children. This raises the population-ethical problem of how total population size should be valued. This paper proposes a methodology to measure the welfare effects of climate change through population and inequality change. We illustrate the methodology using a climate-economy integrated assessment model involving endogenous population change due to climate change-related mortality.

Keywords: Climate change-related mortality, fairness, inequality, population ethics.

JEL Classification numbers: D63, D81.

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1 Introduction

Among its many effects on human well-being, climate change may affect human health and more specifically human mortality (Smith et al., 2014). This is not only a consequence of extreme events (heat waves, floods), this is also due to the prevalence of some diseases, for instance through the exposure to infectious or toxic agents (dengue fever, malaria). A study surveying the existing literature estimated that climate change already causes over 150,000 deaths annually (McMichael et al., 2004). This figure may increase if we cannot avoid dramatic climate change. A recent report for the World Health Organization (Hales et al., 2014) reported an estimate of about 250,000 additional deaths due to climate change per year between 2030 and 2050 due to five causes of death (undernutrition, malaria, dengue, diarrheal diseases and heat).

Hales et al. (2014) also show that these additional deaths are concentrated among people in poorer countries and, for several causes of death, among the young. The impacts of climate change on human mortality thus raise two equity issues: they hit the most deprived in terms of economic resources; they broaden the disparity between the short-lived and the long-lived by increasing early deaths.

The aim of this paper is to examine these equity issues. As argued by Amartya Sen, mortality is a key indicator of economic success and human development. It thus seems crucial to account for mortality in equity and social welfare assessments (Sen, 1998). This requires the construction of well-being metrics that account for (at least) two dimensions of well-being, namely consumption and longevity. The problem of measuring and comparing the well-being of individuals has been a long-lasting and much debated issue in social welfare theory (see Elster and Roemer, 1991, for a book-length discussion of this problem). There are several approaches to how to proceed, including the construction of measures of subjective well-being discussed in a now growing research on happiness. One approach put forward by the theory of fair social choice (Fleurbaey and Maniquet, 2011) is to combine the standard ordinal approach of preferences of welfare economics with the theory of fairness grounding welfare comparisons in the dis-

tribution of goods.

One specificity of the mortality effects of climate change is that they modify the longevity risk of individuals. A seminal result in the literature on social evaluation of risk and uncertainty is the utilitarian aggregation theorem by Harsanyi (1955). Harsanyi's (1955) result was however criticized on two grounds: i) it fails to take into account ex ante inequalities of expected utility (Diamond, 1967), and ii) it fails to take into account ex post inequalities in the distribution of welfare (Fleurbaey, 2010). We may want to consider these two kinds of inequalities (and how they are affected by climate change): the inequality in life expectancies in different social or geographic groups; the inequalities between the long-lived and the short-lived in a given social group.

On top of its direct impact on well-being and inequality, climate change-related mortality may prevent the existence of many future people. Indeed we need to include population size (in particular the size of future generations) in the evaluation of policies. This requires being able to compare situations involving different population sizes. Such comparisons have been discussed in the population ethics literature, following the seminal contribution by Parfit (1984). Although the critical importance of how population is valued has been recognized in the literature (see for instance Millner, 2013; Kolstad et al., 2014), this aspect has hardly been studied (exceptions include Arrow, Dasgupta and Mäler, 2003; Scovronick et al., 2017; Méjean et al., 2017).

The aim of this paper is to assess how climate change-related mortality affects social welfare. Specifically, we set out to measure the welfare effects of climate change through three channels (mortality, inequality, and total population size) and compare them to the usual cost of climate change through damages reducing consumption. To do so, we consider both ex ante and ex post inequalities, and we propose welfare measures that account for these two kinds of inequalities. We also propose a measurement of the welfare effect of total population size by considering several positions from population ethics.

We implement our welfare methodology in a climate integrated assessment model derived from the RICE model of William Nordhaus (Nordhaus, 2010).

The results of this implementation should be interpreted with caution: we only include some causes of climate change-related death; and Nordhaus' damage function has been criticized (Burke, Hsiang and Miguel, 2015; Diaz and Moore, 2017). Our analysis should be taken mainly as an illustration of the welfare methodology, pointing to plausible effects instead of providing precise quantitative results. We find that, although population and inequality effects are generally smaller than consumption effects, they are not negligible in the short run. The effect of climate change on total population size is very small but may also matter in the very long run. The additional effects that we include may also alter policy recommendations. Even though a 2°C policy is typically costly for most generations in the present century when only standard damages are included, the policy can become beneficial to some generations at the end of the century when including mortality, inequality and population size effects (and it is always beneficial to generations in the far future). The losses of generations in the near term are also reduced, especially in the ex post approach. This may alter policy recommendations if sufficient weight is given to the far future.

The paper is organized as follows. In section 2 we justify our approach to welfare measurement by proposing axiomatizations of the social welfare functions used in the paper. In section 3 we apply these welfare models to the evaluation of the effects of climate change through mortality, inequality and population size. Section 4 contains concluding remarks. An appendix provides the proof of our main theorem and additional results of our application.

2 Measuring welfare within a generation

In this section, we discuss how welfare can be measured within a generation when taking into account longevity and the population size of the generation. In the paper, we do not provide an overall assessment of the effects of climate change across generations, but we focus on the effects on each generation (defined as a birth cohort). The formal welfare model we develop in this section could however be applied more generally.

2.1 Framework

Individuals may leave for up to T periods (where $T \in \mathbb{N}$), but they may also die at the end of period $L \leq T$, hence before this maximal lifespan. For each $L \in \{1, \dots, T\}$, denote $\mathbb{L} = \{1, \dots, L\}$. So, an actual (realized) consumption stream for an individual is a vector $c = (c^1, \dots, c^L) \in \mathbb{R}_+^L$, where, for $t \in \mathbb{L}$, $c^t \in \mathbb{R}_+$ is the consumption at age t . We hence denote $\mathcal{C} = \cup_{L=1}^T (\mathbb{R}_+^L)$ the set of all possible actual consumption streams, which includes consumption vectors of different sizes to account for the possibility that people may experience lives with different lengths. The lifespan in a specific vector $c \in \mathcal{C}$ is denoted $l(c)$, where $l(c) = L$ whenever $c \in \mathbb{R}_+^L$. For $L \in \mathbb{T}$, we also denote 1_L the vector $(1, \dots, 1)$ with L components equal to 1. For any $z \in \mathbb{R}_+$, $z \cdot 1_L$ is therefore the vector with L components equal to z .

To make choices under mortality risk, individuals must be able to compare lotteries over \mathcal{C} . People are thus implicitly able to compare lives of different lengths. Let denote $\Delta(\mathcal{C})$ the set of simple lotteries over the set \mathcal{C} .¹ We also abuse notation and denote \mathcal{C} the set of degenerate lotteries assigning probability one to a specific $c \in \mathcal{C}$, and denote c such a lottery.

Each individual i is endowed with preferences that are represented by a complete preorder \succsim^i over $\Delta(\mathcal{C})$. We make the following assumptions on preferences.

Assumption 1 *There exists a continuous and increasing function $u_i : \mathbb{R}_+ \rightarrow \mathbb{R}$ with $u_i(0) \leq 0$ and $\lim_{x \rightarrow \infty} u_i(x) > 0$, and $\beta_i \in (0, 1)$, such that for all $p, q \in \Delta(\mathcal{C})$,*

$$p \succsim_i q \iff \sum_{c \in \mathcal{C}} p(c) U_i(c) \geq \sum_{c \in \mathcal{C}} q(c) U_i(c),$$

where for all for all $c \in \mathcal{C}$

$$U_i(c) = \sum_{\tau=1}^{l(c)} \beta_i^{\tau-1} u_i(c^\tau). \quad (1)$$

¹Thus elements of $\Delta(\mathcal{C})$ are mappings $p : \mathcal{C} \rightarrow [0, 1]$ such that $|\{c \in \mathcal{C} \mid p(c) > 0\}| < +\infty$ (there are finitely many consumption streams with positive probability) and $\sum_{c \in \mathcal{C}} p(c) = 1$.

Assumption 1 implies that individuals are expected utility maximizers. This assumption has long been very standard in the economic literature but most of the recent literature in behavioral economics has suggested that it is not verified empirically. For the purpose of this paper, which focuses on the normative assessment of intertemporal consumption allocations, the assumption may be justified by saying that we only want to take into account individual preferences using the best estimate of the risk that is faced (ruling out the possibility of incorrect or imprecise beliefs). We also exclude behavioral issues such as present bias (hyperbolic discounting).

Let us now look at social allocations of consumption streams. To do so, we need to define possible social outcomes that describe the consumption stream of each individual in the society. For a population with $n \in \mathbb{N}$ individuals, we denote $\mathbf{C}_n = \prod_{i=1}^n \mathcal{C}$: Elements of \mathbf{C}_n are collections $\mathbf{c} = (c_1, \dots, c_n)$ of consumption streams. Importantly, people may have different lifespans L , which is a source of inequality. For $i \neq j$, c_i and c_j may be vectors of different sizes.

Similarly to what we did before, we let $\Delta(\mathbf{C}_n)$ be the set of simple lotteries over \mathbf{C}_n . For any lottery $\mathbf{p} \in \Delta(\mathbf{C}_n)$, we can define the marginal probability distribution p^i over individual i 's consumption stream as follows: for any $c \in \mathcal{C}$, $p_i(c) = \sum_{\mathbf{c} \in \mathbf{C}_n: c_i=c} \mathbf{p}(\mathbf{c})$. Obviously, $p_i \in \Delta(\mathcal{C})$ and it represents the risk faced by individual i when the social prospect is \mathbf{p} .

Now, population size can also vary because we assume that it may be endogenous and change depending on the scenario. So the set of all possible consequences from the social point of view is $\mathbf{C} = \cup_{n \in \mathbb{N}} \mathbf{C}_n$. Similarly, the set of all possible prospects from the social point of view is $\mathbf{P} = \cup_{n \in \mathbb{N}} \Delta(\mathbf{C}_n)$. For any social prospect $\mathbf{p} \in \mathbf{P}$, we denote $N(\mathbf{p})$ the population size in this prospect (i.e. $N(\mathbf{p}) = n$ whenever $\mathbf{p} \in \Delta(\mathbf{C}_n)$). Observe that we assume away any risk on population size. Each prospect is defined for a specific population size.

We assume that there exists a social ranking \succsim of social prospects, which satisfies a minimal continuity requirement.

Assumption 2 *There exists a social welfare ordering \succsim on \mathbf{P} , which is a complete preorder such that, for each $n \in \mathbb{N}$, its restriction to \mathbf{C}_n is continuous.*

2.2 Principles for fair social orderings for variable populations

Let us now consider some principles that may guide how we should evaluate social prospects of mortality and consumption. First, we may want to respect preferences over the length of life and the individual intertemporal allocation of consumption.

Axiom 1 For all $n \in \mathbb{N}$ and for any $\mathbf{p}, \mathbf{q} \in \Delta(\mathbf{C}_n)$, if $p_i \succsim_i q_i$ for all $i \in \{1, \dots, n\}$ then $\mathbf{p} \succsim \mathbf{q}$; if furthermore $p_j \succ_j q_j$ for some $j \in \{1, \dots, n\}$ then $\mathbf{p} \succ \mathbf{q}$.

Axiom 1 is the (strong) ex ante Pareto principle that requires to respect unanimous judgements by all individuals. It is named ‘ex ante’ because it is about ranking prospects rather than known allocations. A weaker version consists in applying the principle only ex post, on sure allocations:

Axiom 2 For all $n \in \mathbb{N}$ and for any $\mathbf{c}, \hat{\mathbf{c}} \in \mathbf{C}_n$, if $c_i \succ_i \hat{c}_i$ for all $i \in \{1, \dots, n\}$ then $\mathbf{c} \succ \hat{\mathbf{c}}$.

In general, we may also want to have rational methods of social decision making. We may thus want to satisfy the following expected utility axiom that may be viewed as a rationality requirement when facing risk.

Axiom 3 There exists a function $U : \mathbf{C} \rightarrow \mathbb{R}$ such that, for all $\mathbf{p}, \mathbf{q} \in \mathbf{P}$:

$$\mathbf{p} \succsim \mathbf{q} \iff \sum_{\mathbf{c} \in \mathbf{C}} \mathbf{p}(\mathbf{c}) U(\mathbf{c}) \geq \sum_{\mathbf{c} \in \mathbf{C}} \mathbf{q}(\mathbf{c}) U(\mathbf{c}).$$

Now we want to introduce fairness principles in the social ranking of prospects. In the fairness literature, transfer principles are usually employed to represent equity concerns. But it is also known that it may be difficult to combine transfer axioms with the Pareto principle in a multidimensional framework (Fleurbaey and Trannoy, 2003; Brun and Tungodden, 2004). We thus follow Fleurbaey, Leroux and Ponthière (2014) and focus on transfers that are made along a constant consumption path when there is no risk.

Axiom 4 For all $n \in \mathbb{N}$ and for all $\mathbf{c}, \tilde{\mathbf{c}} \in \mathbf{C}_n$, if there exists $i, j \in \{1, \dots, n\}$ and $z_i, z_j, \tilde{z}_i, \tilde{z}_j, \varepsilon \in \mathbb{R}_{++}$ such that

1. $\tilde{z}_i + \varepsilon = z_i \leq z_j = \tilde{z}_j - \varepsilon$;
2. $c_i = z_i \cdot 1_T, c_j = z_j \cdot 1_T, \tilde{c}_i = \tilde{z}_i \cdot 1_T, \tilde{c}_j = \tilde{z}_j \cdot 1_T$;
3. $c_k = \tilde{c}_k$ for all $k \in (\{1, \dots, n\} \setminus \{i, j\})$;

then $\mathbf{c} \succsim \tilde{\mathbf{c}}$.

The next axiom is a common independence axiom. It states that indifferent individuals should not have any influence in the social ranking.

Axiom 5 For all $n \in \mathbb{N}$, and for all $\mathbf{c}, \mathbf{c}', \hat{\mathbf{c}}, \hat{\mathbf{c}}' \in \mathbf{C}_n$, if there exists a subset $M \subset \{1, \dots, n\}$ such that:

- $c_j = c'_j$ and $\hat{c}_j = \hat{c}'_j$ for all $j \in M$;
- $c_i = \hat{c}_i$ and $c'_i = \hat{c}'_i$ for all $i \in (\{1, \dots, n\} \setminus M)$;

then $\mathbf{c} \succsim \mathbf{c}'$ if and only if $\hat{\mathbf{c}} \succsim \hat{\mathbf{c}}'$.

For the moment, we have considered populations with a given size. But the policies we consider can modify population size by changing mortality rates of people who can reproduce. This raises the question of population ethics. A natural requirement then is that populations of different sizes can be compared. To obtain this, we propose a principle ensuring that we can always find a population with $n + 1$ individuals that brings as much social welfare as a population with n individuals. Or, put differently, that for any population there is a level of well-being such that, adding a person at this level of well-being is socially indifferent. This well-being level that may depend on the distribution of well-being in the existing population is called a critical level.

Axiom 6 For any $\mathbf{c} \in \mathbf{C}$, there exists $z \in \mathbb{R}_+$ such that, if $\mathbf{c}' \in \mathbf{C}_{n(\mathbf{c})+1}$ is defined by $c'_i = c_i$ for all $i \in \{1, \dots, n(\mathbf{c})\}$ and $c'_{n(\mathbf{c})+1} = z \cdot 1_T$, then $\mathbf{c} \sim \mathbf{c}'$.

In addition to the existence of a critical level, we may want to avoid situations where increasing population size may eventually reduce social welfare even if everyone enjoys a high level of consumption, a long life, and there is no inequality. The next principle avoids such a situation.

Axiom 7 *There exists $z \in \mathbb{R}_+$ such that, for any $n \in \mathbb{N}$, if $\mathbf{c} \in \mathbf{C}_n$ is defined by $c_i = z \cdot 1_T$ for all $i \in \{1, \dots, n\}$, and $\mathbf{c}' \in \mathbf{C}_{n+1}$ is defined by $c'_i = z \cdot 1_T$ for all $i \in \{1, \dots, n+1\}$, then $\mathbf{c}' \succsim \mathbf{c}$.*

Last we impose two regularity conditions. First we may want that only relative population size be significant (see Blackorby, Bossert and Donaldson, 2002, page 165). This is guaranteed by a replication invariance principle: if we compare two situations \mathbf{c}, \mathbf{c}' for a generation, then it is the same as comparing two situations $\hat{\mathbf{c}}, \hat{\mathbf{c}}'$ for k generations provided they correspond in all generations to \mathbf{c} and \mathbf{c}' .

Axiom 8 *For all $\mathbf{c}, \mathbf{c}' \in \mathbf{C}$, for all $k \in \mathbb{N}$, if $\mathbf{c}, \mathbf{c}' \in \mathbf{C}$ are such that:*

- $n(\hat{\mathbf{c}}) = k \times n(\mathbf{c})$, $n(\hat{\mathbf{c}}') = k \times n(\mathbf{c}')$;
- for all $m \in \{1, \dots, n(\mathbf{c})\}$ and for all $l \in \{1, \dots, k\}$, $\hat{c}_{k(m-1)+l} = c_m$;
- for all $m \in \{1, \dots, n(\mathbf{c}')\}$ and for all $l \in \{1, \dots, k\}$, $\hat{c}'_{k(m-1)+l} = c'_m$;

then $\mathbf{c} \succsim \mathbf{c}' \iff \hat{\mathbf{c}} \succsim \hat{\mathbf{c}}'$.

Second, we may want that only the relative level of consumption matters for social judgements so that, in particular, the choice of a currency for the measurement of consumption does not matter. This is possible if we have a ratio-scale form of measurement. The next axiom guarantees that this is the case.

Axiom 9 *For any $n \in \mathbb{N}$, for any $\lambda \in \mathbb{R}_{++}$, and for all $(z_1, \dots, z_n), (\hat{z}_1, \dots, \hat{z}_n) \in \mathbb{R}_+^n$, $(z_1 \cdot 1_T, \dots, z_n \cdot 1_T) \succsim (\hat{z}_1 \cdot 1_T, \dots, \hat{z}_n \cdot 1_T)$ if and only if $(\lambda z_1 \cdot 1_T, \dots, \lambda z_n \cdot 1_T) \succsim (\lambda \hat{z}_1 \cdot 1_T, \dots, \lambda \hat{z}_n \cdot 1_T)$.*

2.3 Individual well-being and a characterization result

The construction of individual measures of well-being is a hotly debated topic. In this paper, we rely on the theory of fair social choice that uses the individuals' preference orderings without assuming that comparisons of utility levels are possible (Fleurbaey and Maniquet, 2011). With the axioms proposed above, we actually obtain individual measures of well-being similar to those in Fleurbaey, Leroux and Ponthière (2014). They obtained a criterion that they call the maximin of the “Constant consumption profile equivalent on the reference lifespan”. This is exactly the criterion we obtain for sure outcomes, the difference being that we get a specific reference lifespan, namely the maximal one.

Definition 1 *For any $i \in \mathbb{N}$ and any $c_i \in \mathcal{C}$, the Constant consumption profile equivalent for a long life $e_i(c_i) \in \mathbb{R}_+$ of c_i is the level of consumption such that*

$$e_i(c_i) \cdot 1_T \sim_i c_i.$$

Given Assumption 1, we have:

$$e_i(c_i) = u_i^{-1} \left(\frac{1-\beta}{1-\beta^T} \sum_{\tau=1}^{l(c_i)} \beta_i^{\tau-1} u_i(c_i^\tau) \right)$$

It is important to realize that such a constant consumption profile equivalent for a long life always exists because of Assumption 1. Indeed, Assumption 1 implies that for any $c \in \mathcal{C}$, $U_i(0 \cdot 1_T) \leq U_i(c) \leq \lim_{x \rightarrow \infty} U_i(x \cdot 1_T)$ (because $u_i(0) \leq 0$, $\lim_{x \rightarrow \infty} u_i(x) > 0$ and u_i is increasing). Therefore, by continuity, it is always possible to compare actual consumption paths to a constant consumption plan with the longest possible longevity.

Constant consumption profile equivalent for a long life are ex post measures of well-being (when the risk has been realized). We may want to also consider an ex ante measure. We name it the certainty-equivalent constant consumption.

Definition 2 *For any $i \in \mathbb{N}$ and any $p_i \in \Delta(\mathcal{C})$, the certainty equivalent constant consumption $ce_i(p_i) \in \mathbb{R}_+$ of p_i is the level of consumption such that*

$$ce_i(p_i) \cdot 1_T \sim_i p_i.$$

Given Assumption 1, we have:

$$ce_i(p_i) = u_i^{-1} \left(\frac{1-\beta}{1-\beta^T} \sum_{c \in \mathcal{C}} p_i(c) \left[\sum_{\tau=1}^{L(c)} \beta_i^{\tau-1} u_i(c^\tau) \right] \right)$$

For the same reason as above, we know that given Assumption 1 the certainty equivalent constant consumption is well-defined for any individual prospect $p_i \in \Delta(\mathcal{C})$.

With these two definitions, we can state our main characterization result.

Theorem 1

1. If the social ordering \succsim satisfies Axiom 1 and Axioms 4–9, then there exist $\varepsilon, \theta \in \mathbb{R}_+$ such that, for all $\mathbf{p}, \mathbf{q} \in \mathbf{P}$, $\mathbf{p} \succsim \mathbf{q} \iff W_{ea}(\mathbf{p}) \geq W_{ea}(\mathbf{q})$, where

$$W_{ea}(\mathbf{p}) = [n(\mathbf{p})]^\theta \times \left(\frac{1}{n(\mathbf{p})} \sum_{i=1}^{n(\mathbf{p})} (ce_i(p_i))^{1-\varepsilon} \right)^{\frac{1}{1-\varepsilon}} \quad \forall \mathbf{p} \in \mathbf{P}.$$

2. If the social ordering \succsim satisfies Axioms 2–9, then there exist $\varepsilon, \theta \in \mathbb{R}_+$ and a continuous and increasing function $\Psi : \mathbb{R}_+ \rightarrow \mathbb{R}$ such that, for all

$\mathbf{p}, \mathbf{q} \in \mathbf{P}$, $\mathbf{p} \succsim \mathbf{q} \iff W_{ep}(\mathbf{p}) \geq W_{ep}(\mathbf{q})$, where²

$$W_{ep}(\mathbf{p}) = \sum_{\mathbf{c} \in \mathbf{C}_n} \mathbf{p}(\mathbf{c}) \times \Psi \left[[n(\mathbf{c})]^\theta \times \left(\frac{1}{n(\mathbf{c})} \sum_{i=1}^{n(\mathbf{c})} (e_i(c_i))^{1-\varepsilon} \right)^{\frac{1}{1-\varepsilon}} \right] \quad \forall \mathbf{p} \in \mathbf{P}.$$

Theorem 1 proposes two fair approaches in evaluating social welfare for same population cases. The ex-ante approach (1.) uses ex ante well-being metrics for individuals and aggregates them through an additively separable (prioritarian) formula. Parameter ε is the coefficient of inequality aversion that controls social preferences for redistribution. In this ex ante approach, individual risk aversion plays a key role because we satisfy the Pareto property. The equally distributed equivalent is multiplied by population size to the power θ , where θ is a population ethics parameter discussed below.

The ex-post approach (2.) first aggregates individuals' ex-post well-being through the additively separable formula in final situations and then takes an expectation of the transformed ex-post social welfare multiplied by population size to the power θ . Parameter ε is again the coefficient of inequality aversion. Individuals' risk aversion does not matter, but we can satisfy the social rationality requirements encapsulated in the social expected utility hypothesis.

Observe that the two approaches collapse to the same formula when there is no risk. In that case, we obtain a prioritarian social welfare function for situations where population size may change. To understand the population ethics parameter it is convenient to consider the case $\varepsilon = 0$ that corresponds to a case

²In the limit case $\varepsilon = 1$, we actually have:

$$W_{ea}(\mathbf{p}) = [n(\mathbf{p})]^\theta \times \left(\prod_{i=1}^{n(\mathbf{p})} (ce_i(p_i))^{\frac{1}{n(\mathbf{p})}} \right) \quad \forall \mathbf{p} \in \mathbf{P}$$

and

$$W_{ep}(\mathbf{p}) = \sum_{\mathbf{c} \in \mathbf{C}_n} \mathbf{p}(\mathbf{c}) \times \Psi \left[[n(\mathbf{c})]^\theta \times \left(\prod_{i=1}^{n(\mathbf{c})} (e_i(c_i))^{\frac{1}{n(\mathbf{c})}} \right) \right] \quad \forall \mathbf{p} \in \mathbf{P}.$$

similar to utilitarianism. Indeed, ever since the seminal work by Parfit (1984), population ethics has been mostly discussed in the utilitarian framework. Parfit considered two opposite versions of Utilitarianism: Total Utilitarianism (which is simply a sum of well-being numbers like in our equations above) and Average Utilitarianism that divides the sum by the number of people. In our framework, they would correspond to the cases $\theta = 1$ and $\theta = 0$. Parfit showed that these two formulas imply paradoxes and disturbing conclusions. To amend these versions of utilitarianism, Ng (1989) proposed Number-dampened Utilitarianism that multiplies average utility by a function depending of population size to limit the value of large populations. We partly recover these intermediate cases with $0 < \theta < 1$.

3 An application to climate change

3.1 *A numerical Integrated Assessment Model*

To translate climate policies into social prospects to be evaluated, we use an Integrated Assessment Model (IAM). More specifically, we modify a leading IAM, Regional Integrated model of Climate and the Economy (RICE)³, to include climate change-related mortality. RICE is a regional IAM that divides the world into 12 regions. To fit the regional data on mortality impacts, we use a regional models with 6 regions to match regions in Hales et al. (2014) and data from the UN World Population Prospects (WPP). We thus have recalibrated the RICE model accordingly.⁴

In this paper, the IAM is used to project scenarios corresponding to three possible policy pathways in the future. We consider three climate policy scenarios that are related to three different emission trajectories. In the “Business as usual” (henceforth BAU) scenario, there is no control of greenhouse gas (henceforth GHG) emissions: the GHG stock builds up rapidly in the atmosphere and climate change is substantial. The 2 °C and 3 °C scenarios correspond to two stabilisation

³RICE was developed by William Nordhaus (see Nordhaus, 2010, for a presentation of the model).

⁴For more details, see Appendix A.2.

policies that control GHG emissions so as to stabilize global temperature increase (see Appendix A.2.2 for details).

We compute welfare losses in each period in the future until year 2100. To do so, we consider each period t as a generation and compute a measure of the welfare of the generation born in t (not of the overall population living in period t). The social welfare criteria presented in section 2 would require to consider individual lifetimes that span across several periods: a person born in t would live in $t + 1$, $t + 2$, etc, so that her well-being depends on consumption and mortality in these future periods. To avoid non-separability between periods, we compute instead in each period t *stationary equivalent levels of welfare*, that is the levels of welfare for the generation born in t that would be obtained if the conditions prevailing in period t would hold for this generation along its lifespan. This is similar to the period life expectancy (as opposed to the cohort life expectancy) that is commonly used in demography.

To include inequality, we consider six regions: Africa, Asia, Europe, Latin America, Northern America and Oceania. The outcome of a specific scenario in period t thus consists in three components: the population vector $(n_k^t)_{k=1,\dots,6}$, where n_k^t is the total population in region k and period t ; the consumption vector $(x_k^t)_{k=1,\dots,6}$, where x_k^t is the average consumption in region k and period t ; a collection of functions $(\pi_k^t)_{k=1,\dots,6}$, where each π_k^t is a function $\pi_k^t : \mathbb{T} \rightarrow [0, 1]$ that gives the probability $\pi_k^t(L)$ that a person in region k lives exactly L years (T is the maximal age as before).⁵ For each period t and each region k , $\sum_{L=1}^T \pi_k^t(L) = 1$. All people in a given region and generation have the same constant per capita consumption and face the same mortality prospect. We denote $n^t = \sum_{k=1}^6 n_k^t$ the total population in period t in the scenario. A scenario in period t , denoted s^t , is thus completely described by $s^t = ((n_k^t)_{k=1,\dots,6}, (x_k^t)_{k=1,\dots,6}, (\pi_k^t)_{k=1,\dots,6})$.⁶

⁵These probabilities are inferred from the current mortality table at time t : we do as if the mortality table remains constant along the life of people in generation t .

⁶To relate our description here with the framework in Section 1, remark that a scenario implies that possible consumption streams for individuals in region k at time t are of the form $x_k^t \cdot 1_L$, with $L \in \mathbb{T}$. And the prospect of these n_k^t individuals is p_k^t such that $p_k^t(x_k^t \cdot 1_L) = \pi_k^t(L)$ for all $L \in \mathbb{T}$ and 0 otherwise.

To compute individual well-being levels, we make specific assumptions on the form of the utility function u_i in Equation (1). We follow Becker, Philipson and Soares (2005) and assume that $u(c) = \frac{c^{1-\gamma}}{1-\gamma} - \alpha(c)$. However, and contrary to Becker, Philipson and Soares (2005), we do not take $\alpha(c)$ (the critical-level of existence) to be independent of c . Indeed, following a meta-analysis of values of statistical lives (henceforth VSL) carried out by Miller (2000), we assume that VSL is proportional to income. To obtain such a proportionality, we assume that $\alpha(c) = \frac{(\kappa c)^{1-\gamma}}{1-\gamma}$, where $0 < \kappa < 1$. Hence, along a constant consumption path at level x_k^t , we obtain that

$$\bar{e}(x_k^t, L) = e(x_k^t \cdot 1_L) = x_k^t \left(\frac{1-\beta^L}{1-\beta^T} + \frac{\beta^T - \beta^L}{1-\beta^T} \kappa^{1-\gamma} \right)^{\frac{1}{1-\gamma}},$$

and⁷

$$\bar{ce}(x_k, \pi_k^t) = ce(p_k^t) = x_k \left(\sum_{L=1}^T \pi_k^t(L) \left(\frac{1-\beta^L}{1-\beta^T} + \frac{\beta^T - \beta^L}{1-\beta^T} \kappa^{1-\gamma} \right) \right)^{\frac{1}{1-\gamma}}.$$

Denote $\ell_{ep}(L) = \left(\frac{1-\beta^L}{1-\beta^T} + \frac{\beta^T - \beta^L}{1-\beta^T} \kappa^{1-\gamma} \right)^{\frac{1}{1-\gamma}}$ and $\ell_{ea}(\pi_k^t) = \left(\sum_{L=1}^T \pi_k^t(L) [\ell_{ep}(L)]^{1-\gamma} \right)^{\frac{1}{1-\gamma}}$, we thus have $\bar{e}(x_k^t, L) = x_k^t \ell_{ep}(L)$ and $\bar{ce}(x_k^t, \pi_k^t) = x_k^t \ell_{ea}(\pi_k^t)$. We follow Becker, Philipson and Soares (2005) and choose $\gamma = 0.83$ and $\beta = e^{-0.03}$. Regarding κ , we use Miller's (2000) rule of thumb (based on his extensive review of 68 studies estimating VSL) that VSL amounts to approximately 150 times GDP per capita. From this, we inferred $\kappa = 0.05$.

Using these simple definitions of individual well-being, we can use the results in Theorem 1 to measure social welfare for generation t (in our setting: in period t). Before introducing the formulas, let us mention one additional assumption. We consider that the population in each region and each generation is large enough so that the probability $\pi_k^t(L)$ that an individual in generation t and region k lives for exactly L periods is the same as the proportion of individuals in that generation t and that region k who *actually* live for L periods. So, in the ex post approach,

⁷Where p_k^t is such that $p_k^t(x_k^t \cdot 1_L) = \pi_k^t(L)$ for all $L \in \mathbb{T}$ and 0 otherwise.

the society actually faces no risk: the numbers of people at each welfare levels is known for sure. We know for instance that $n_k^t \pi_k^t(L)$ individuals will have an ex post well-being level of $\bar{e}(x_k^t, L)$ (that is the level of well-being for people in generation t and region k who live for exactly L periods).

So, to any scenario s^t , we can associate the following welfare levels :

1. Ex ante social welfare:

$$\begin{aligned}\hat{W}_{ea}(s^t) &= [n^t]^\theta \times \left(\sum_{k=1}^6 \frac{n_k^t}{n^t} (\bar{ce}(x_k^t, \pi_k^t))^{1-\varepsilon} \right)^{\frac{1}{1-\varepsilon}} \\ &= [n^t]^\theta \times \mu_x(s^t) \times \mu_{ea}^\ell(s^t) \times \frac{\mu_{ce}(s^t)}{\mu_x(s^t) \mu_{ea}^\ell(s^t)} \times E_{ea}(s^t),\end{aligned}\quad (2)$$

where $\mu_x(s^t) = \sum_{k=1}^6 \frac{n_k^t}{n^t} x_k^t$ is average per capita consumption, $\mu_{ea}^\ell(s^t) = \sum_{k=1}^6 \frac{n_k^t}{n^t} \ell_{ea}(\pi_k^t)$ is the average life expectancy coefficient, $\mu_{ce}(s^t) = \sum_{k=1}^6 \frac{n_k^t}{n^t} \bar{ce}(x_k^t, \pi_k^t)$ is the average certainty equivalent consumption, and $E_{ea}(s^t) = \left(\sum_{k=1}^6 \frac{n_k^t}{n^t} \left(\frac{\bar{ce}(x_k^t, \pi_k^t)}{\mu_{ce}(s^t)} \right)^{1-\varepsilon} \right)^{\frac{1}{1-\varepsilon}}$ is an ex ante equality index.

2. Ex post social welfare:

$$\begin{aligned}\hat{W}_{ep}(s^t) &= [n^t]^\theta \times \left(\sum_{k=1}^6 \sum_{L=1}^T \frac{\pi_k^t(L) n_k^t}{n^t} (\bar{e}(x_k^t, L))^{1-\varepsilon} \right)^{\frac{1}{1-\varepsilon}} \\ &= [n^t]^\theta \times \mu_x(s^t) \times \mu_{ep}^\ell(s^t) \times \frac{\mu_e(s^t)}{\mu_x(s^t) \mu_{ep}^\ell(s^t)} \times E_{ep}(s^t),\end{aligned}\quad (3)$$

where $\mu_{ep}^\ell(s^t) = \sum_{k=1}^6 \sum_{L=1}^T \frac{\pi_k^t(L) n_k^t}{n^t} \ell_{ep}(L)$ is the average realized life coefficient, $\mu_e(s^t) = \sum_{k=1}^6 \sum_{L=1}^T \frac{\pi_k^t(L) n_k^t}{n^t} \bar{e}(x_k^t, L)$ is the average realized equivalent consumption, and $E_{ep}(s^t) = \left(\sum_{k=1}^6 \sum_{L=1}^T \frac{\pi_k^t(L) n_k^t}{n^t} (\bar{e}(x_k^t, L))^{1-\varepsilon} \right)^{\frac{1}{1-\varepsilon}}$ is an ex post equality index.

In our baseline scenarios, whose results are presented in the next section, we take $\varepsilon = 1$ and $\theta = 1$. A sensitivity analysis of the results to these choices is presented in Appendix A.3.2. Table 1 summarizes the main parameters used in our analysis.

Table 1: Parameters of the numerical model

Parameter	Value	Source	
Individual preferences			
γ	Inverse intertemporal elasticity of substitution	0.83	Becker, Philipson and Soares (2005)
β	Discount factor	$e^{0.03}$	Becker, Philipson and Soares (2005)
κ	Neutrality-level parameter	0.05	Calibrated on Miller (2000)
Normative parameters			
A^*	Reference age	90	
ε	Inequality aversion parameter	1	
θ	Population ethics parameter	1	

3.2 Results

3.2.1 Measuring the welfare effects of climate change

We want first to measure the effects of climate change on social welfare. Consider two scenarios in period t , s^t and \hat{s}^t . The welfare loss (or gain, if the quantity is negative) in scenario \hat{s}^t compared to scenario s^t can be measured by $\Delta_{ea}(s^t, \hat{s}^t) = 1 - \frac{\hat{W}_{ea}(\hat{s}^t)}{\hat{W}_{ea}(s^t)}$ in the ex ante case and $\Delta_{ep}(s^t, \hat{s}^t) = 1 - \frac{\hat{W}_{ep}(\hat{s}^t)}{\hat{W}_{ep}(s^t)}$ in the ex post case. Given that \hat{W}_{ea} and \hat{W}_{ep} are linear in average consumption, Δ_{ea} and Δ_{ep} also correspond to the equivalent percent loss in average consumption in one scenario compared to the other.

Using Equation 3, we obtain:

$$\begin{aligned} \Delta_{ea}(s^t, \hat{s}^t) &= 1 - \frac{[\hat{n}^t]^\theta \times \mu_x(\hat{s}^t) \times \mu_{ea}^\ell(\hat{s}^t) \times \frac{\mu_{ce}(\hat{s}^t)}{\mu_x(\hat{s}^t) \mu_{ea}^\ell(\hat{s}^t)} \times E_{ea}(\hat{s}^t)}{[n^t]^\theta \times \mu_x(s^t) \times \mu_{ea}^\ell(s^t) \times \frac{\mu_{ce}(s^t)}{\mu_x(s^t) \mu_{ea}^\ell(s^t)} \times E_{ea}(s^t)} \\ &= \underbrace{1 - \frac{[\hat{n}^t]^\theta}{[n^t]^\theta}}_{\text{population}} + \underbrace{1 - \frac{\mu_x(\hat{s}^t)}{\mu_x(s^t)}}_{\text{damages}} + \underbrace{1 - \frac{\mu_{ea}^\ell(\hat{s}^t)}{\mu_{ea}^\ell(s^t)}}_{\text{mortality}} + \underbrace{1 - \frac{E_{ea}(\hat{s}^t)}{E_{ea}(s^t)}}_{\text{inequality}} + \underbrace{I_{ea}(s^t, \hat{s}^t)}_{\text{interaction}} \end{aligned}$$

Similarly,

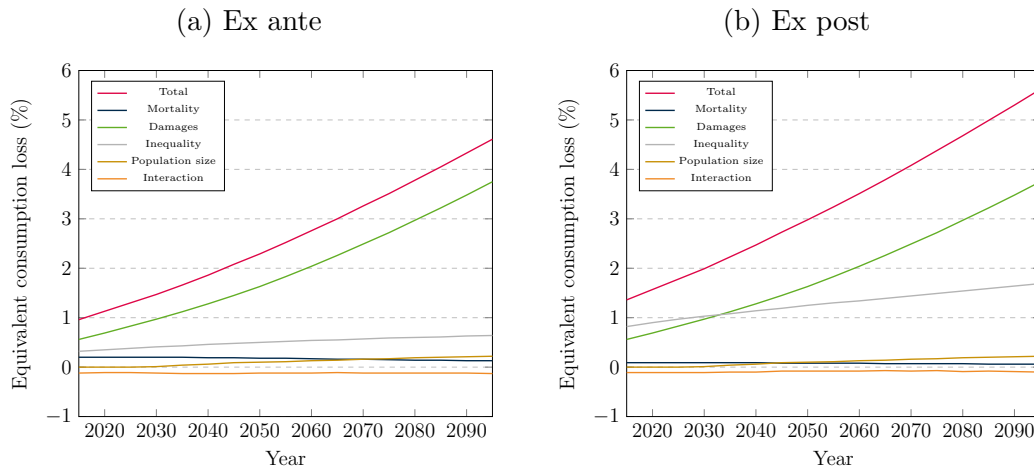
$$\Delta_{ep}(s^t, \hat{s}^t) = \underbrace{1 - \frac{[\hat{n}^t]^\theta}{[n^t]^\theta}}_{\text{population}} + \underbrace{1 - \frac{\mu_x(\hat{s}^t)}{\mu_x(s^t)}}_{\text{damages}} + \underbrace{1 - \frac{\mu_{ep}^\ell(\hat{s}^t)}{\mu_{ep}^\ell(s^t)}}_{\text{mortality}} + \underbrace{1 - \frac{E_{ep}(\hat{s}^t)}{E_{ep}(s^t)}}_{\text{inequality}} + \underbrace{I_{ep}(s^t, \hat{s}^t)}_{\text{interaction}}$$

The above formulas give a decomposition of the total welfare loss (expressed as a percentage of average consumption) in four parts: the part due to total population loss (“population”), the part due to standard climate damages represented in the damage function (“damages”), the part due to additional average mortality (“mortality”) and the part due to an increase in inequality because damages and climate change-related mortality are not distributed equally (“inequality”). There is an additional interaction term between those components.

In this section, we seek to measure the welfare effects of climate change. To do so, we compare in the BAU case a scenario where climate damages, endogenous mortality and population change are taken into account to a scenario where we remove climate damages and use the exogenous baseline population dynamics. Using the decomposition formulas above, we can assess the equivalent consumption loss (as a percent of the exogenous average consumption level) due to climate damages, mortality, inequality and population size. These results are presented in Figure 1.

Panel (a) in Figure 1 shows the equivalent consumption loss due to climate in the BAU scenario for the ex ante approach. In the short run, the impacts on mortality are a significant part of overall impacts although they amount to about 0.2% of average consumption per capita. Similarly, inequality is important in the short-run and its the impact is quite stable through time (0.32% to 0.64% of average consumption per capita). The standard climate damages on consumption and production are on the contrary very much increasing through from a value of 0.56% to a value of 3.75% of average consumption per capita. The effect of the loss in total population size is inexistent in the first few periods but then increases because of the cumulative effects (people dying early are not having children, and these unborn children in turn do not have children, etc.). In total, the non-standard damages represent an equivalent loss of 0.40% to 0.70%, which

Figure 1: Equivalent welfare loss from climate change in BAU



is not negligible. As a percent of total loss (including standard damages) they amount to about 50% in the short run and then decrease to 20% at the end of the century.

Panel (b) in Figure 1 shows the equivalent consumption loss due to climate in the BAU scenario for the ex post approach. As indicated in our decomposition equations above, the damage and total population effects are the same in the ex ante and the ex post cases. Panel (b) in Figure 1 shows that the effect of climate change on inequality is larger in the ex post approach: it rises from 0.82% in the short run (more than the effect of damages) to 1.69% at the end of the century. It should be noted that our inequality indices are multidimensional, as they combine the inequality in consumption and the inequality in mortality (as well as the correlation between the two that increases inequality further). The change we measure here is thus the additional inequality (in these two dimensions) due to climate change. In the ex ante and ex post approaches, the inequality in consumption is the same, so the difference between the two arises from the inequality in mortality. In the ex post approach, we look at inequalities in actual lifespans: so having some more young people dying from climate change has a large effect on inequality, which explains the effect we observe. On the contrary,

the average mortality effect is lower in the ex post than in the ex ante approach, around 0.06% for the whole period. In the end, the total effect is larger in the ex post approach although the patterns are similar.

These findings would be also true in the 3°C and 2°C scenarios (see Appendix A.3.1). Appendix A.3.2 also presents the sensitivity of these results to the level of inequality aversion and the population ethics parameter θ . It appears in particular that the inequality effect can become large (more that 2% of consumption per capita) in the ex post case.

3.3 *Climate change, welfare, population and climate policy*

For the moment, we have studied the size of the mortality, inequality and population losses related to climate change. One may wonder if these additional losses may modify the appeal of climate policy. In this section, we aim at studying this question by comparing a 2°C policy scenarios to the BAU (see Appendix A.3.3 for the comparison between a 3°C scenario and the BAU). In all scenarios, we include climate damages and use our endogenous population structure. We use the same decomposition formulas as in section 3.2.1.

Figure 2: Equivalent welfare gains / losses from a 2°C policy compared to BAU

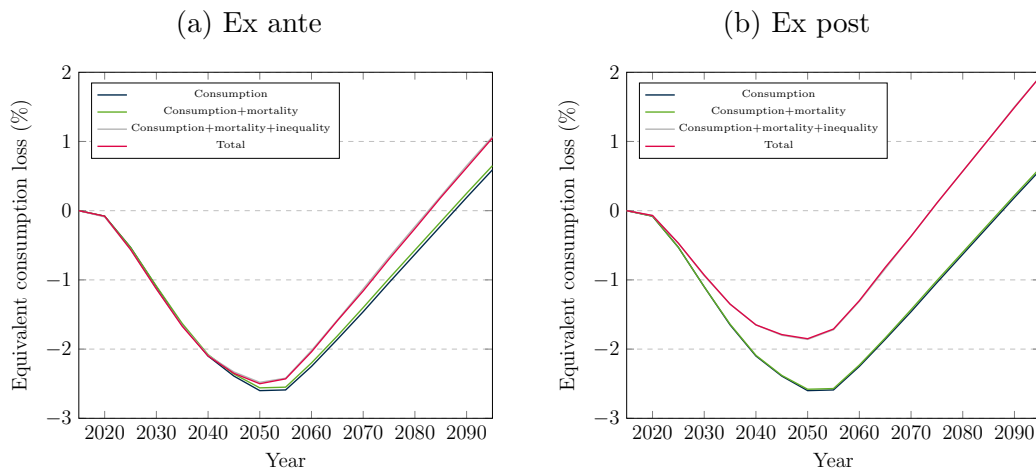


Figure 2 displays those results. In panel (a), we see the welfare change in the 2°C scenario compared to the BAU scenario using the ex ante approach. When only consumption per capita is considered (curve “Consumption”), there is a small welfare cost for the first generations, but then this cost increases to up to 2.6% of consumption per capita in 2050 before the cost decrease. Small welfare gains only occur in 2090. Adding mortality (curve “Consumption+mortality”) does not modify the appeal of the 2°C policy. Adding inequality does (curve “Consumption+mortality'+inequality’): it slightly reduces the losses in mid-century (2.4% of consumption per capita in 2050) but mainly improves the situation of generations at the end of the century. Welfare gains then start occurring in 2085. Adding the effect of total population (and the interaction effect) makes no difference.

Results are more striking with the ex post approach (Figure 2, panel (b)). The curve with damages only is the same as in the ex ante case. And like in the ex ante case, the average mortality effect, population size effect and interaction effect are very small. But the inequality effect (including reduced inequalities in mortality) is stronger. The maximal loss (in 2050) is then 2.4% of consumption per capita and welfare gains start occurring in 2075. The inequality effect therefore increases the appeal of the 2°C scenario, especially given that more gains are expected for generations in the next century (not displayed here). Whether this is sufficient to prefer a 2°C scenario will depend on how we balance the interest of different generations (including the question of discounting). We can only say that including the non-consumption effects (especially inequality) goes in the direction of favoring more ambitious climate policy.

4 Conclusion

In this paper, we have measured the welfare losses related to the impact of climate change on mortality and population size. We have developed methods to combine these mortality and population size effects to consumption into a social welfare measure. In particular, we have characterized two broad families of social wel-

fare functions: the ex ante social welfare functions based on certainty-equivalent consumption well-being measures, and ex post social welfare functions looking at actual life spans of individuals. These measures can be used to decompose social welfare into average consumption, an average mortality index, inequality and total population size (plus some interaction effects).

Using an Integrated Assessment Model, we have showed that the non consumption effects can play a big role. They represent a significant part of the welfare losses due to climate change (up to more than 50% in the near-term for the ex post approach). They can alter policy recommendation by increasing the appeal of policies aiming at limiting the emissions of greenhouse gases. We have showed that inequality plays a big role, where inequality combines the effects of consumption and mortality. A big issue with climate change is that it increases both kinds of inequalities.

This paper is a first attempt to measure the multiple aspects of climate change using an integrative and coherent social welfare approach. There are several aspects that we do not take into account or only partially. The effects on mortality are only those related to five causes of death and do not account for instance for extreme weather events (hurricanes, floods). They also do not account for possible increases in conflicts or losses related to climate migrations. There also many other non consumption effects of climate change that we do not account for, for instance the impacts on biodiversity and wild animals populations. Many of these interesting issues could be tackled in future work.

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A Appendix

A.1 Appendix A: Proof of the Theorem

A.1.1 Preliminary results

We consider a complete preorder R over $\cup_{n \in \mathbb{N}} \mathbb{R}_+^n$ (with typical elements $u = (u_1, \dots, u_n)$ or $v = (v_1, \dots, v_n)$). P denotes the asymmetric part of R and I its symmetric part. For any $u \in \cup_{n \in \mathbb{N}} \mathbb{R}_+^n$, we denote $n(u)$ the number of components of vector u , that is $n(u) = n$ whenever $u \in \mathbb{R}_+^n$. Let us define four properties.

Continuity. For any $n \in \mathbb{N}$, and for all $u \in \mathbb{R}_+^n$, the sets $\{v \in \mathbb{R}_+^n \mid u R v\}$ and $\{v \in \mathbb{R}_+^n \mid v R u\}$ are closed.

Monotonicity. For any $n \in \mathbb{N}$, and for all $u, v \in \mathbb{R}_+^n$, if $u \gg v$ then $u P v$.

Transfer. For any $n \in \mathbb{N}$, and for all $u, v \in \mathbb{R}_+^n$, all $\delta > 0$ and any $i, j \in N$, if $u_i = v_i - \delta \geq v_j + \delta = v_j$ and $x_k = y_k$, for all $k \in N \setminus \{i, j\}$ then $u P v$.

Separability. For any $n \in \mathbb{N}$, and for all $u, v, \hat{u}, \hat{v} \in \mathbb{R}_+^n$, if there exists a subset $M \subset \{1, \dots, n\}$ such that:

- $u_j = v_j$ and $\hat{u}_j = \hat{v}_j$ for all $j \in M$;
- $u_i = \hat{u}_i$ and $v_i = \hat{v}_i$ for all $i \in (\{1, \dots, n\} \setminus M)$;

then $u R v \iff \hat{u} R \hat{v}$.

Let us introduce additional notation and terminology. For any $n \in \mathbb{N}$ and for any $u \in \mathbb{R}_+^n$, a k -replica of u , denoted $k \star u$ is a vector $v \in \mathbb{R}_+^{kn}$ such that, for all $m \in \{1, \dots, n\}$ and for all $l \in \{1, \dots, k\}$, $v_{k(m-1)+l} = u_m$. For any $n \in \mathbb{N}$, for any $u \in \mathbb{R}_+^n$ and for any $\lambda \in \mathbb{R}_{++}$, denote λu the vector $v \in \mathbb{R}_+^n$ such that, for all $i \in \{1, \dots, n\}$, $v_i = \lambda u_i$.

Replication invariance. For all $u, v \in \cup_{n \in \mathbb{N}} \mathbb{R}_+^n$, for all $k \in \mathbb{N}$, $u R v$ if and only if $k \star u R k \star v$.

Scale invariance. For any $n \in \mathbb{N}$, for all $u, v \in \mathbb{R}_+^n$, and for all $\lambda \in \mathbb{R}_{++}$, $u R v$ if and only if $\lambda u R \lambda v$.

We obtain the following result.

Proposition 1 *If a complete quasi-ordering R over $\cup_{n \in \mathbb{N}} \mathbb{R}_+^n$ satisfies Continuity, Monotonicity, Transfer, Separability, Replication invariance and Scale invariance, then for each $n \in \mathbb{N}$ there exists $\varepsilon \in \mathbb{R}_+$ such that, for all $u, v \in \mathbb{R}_+^n$, $u R v$ if and only if⁸*

$$\sum_{i=1}^n \frac{u_i^{1-\varepsilon}}{1-\varepsilon} \geq \sum_{i=1}^n \frac{v_i^{1-\varepsilon}}{1-\varepsilon}.$$

Proof. Consider any $n \in \mathbb{N}$ with $n \geq 3$. Separability implies the Independence property in Debreu (1960, Definition 4). Further, each coordinate of \mathbb{R}_+^n is essential in the sense of Debreu (1960) because \succsim satisfies Monotonicity. Thus, given that R also satisfies continuity, it follows from Theorem 3 in Debreu (1960) that there exist n continuous and increasing real-valued functions $\phi_1^n, \dots, \phi_n^n$ on \mathbb{R}_+ such that for all $u, v \in \mathbb{R}_+^n$, $u R v$ if and only if

$$\sum_{i=1}^n \phi_i^n(u_i) \geq \sum_{i=1}^n \phi_i^n(v_i).$$

Furthermore, this representation is unique up to a positive affine transformation.

By Lemma 2 in Fleurbaey and Zuber (2013), given that R satisfies Transfer, R must also satisfy an Anonymity property that implies that $\phi_i^n = \phi_j^n = \phi^n$ for all $i, j \in \{1, \dots, n\}$. Furthermore, Transfer implies that ϕ^n must be weakly concave.

By scale invariance, we obtain that, for any $\lambda \in \mathbb{R}_+$, and for all $u, v \in \mathbb{R}_+^n$,

$$\sum_{i=1}^n \phi^n(u_i) \geq \sum_{i=1}^n \phi^n(v_i) \iff \sum_{i=1}^n \phi^n(\lambda u_i) \geq \sum_{i=1}^n \phi^n(\lambda v_i).$$

Given that the additive representation is unique up to a positive affine transformation, we must have $\phi^n(\lambda z) = a(\lambda)\phi^n(z) + b(\lambda)$ for all $z, \lambda \in \mathbb{R}_+$. Let us define

⁸In the case $\varepsilon = 1$, we actually have $u R v$ if and only if $\sum_{i=1}^n \ln(u_i) \geq \sum_{i=1}^n \ln(v_i)$.

real-valued functions f, g, h on \mathbb{R}_+ as follows:

$$f(z) = \phi^n(e^z), \quad g(z) = a(e^z), \quad h(z) = b(e^z).$$

We obtain the following functional equation for $x, y \in \mathbb{R}$:

$$f(x + y) = g(x)f(y) + h(x).$$

Given that f is strictly increasing, solutions to the above functional equations are characterized in Corollary 1 in Section 3.1.3 of Aczél (2006). These solutions imply that there exist constant $\alpha^n \in \mathbb{R}_+$ and $\beta^n, \varepsilon^n \in \mathbb{R}$ such that either:

$$f(z) = \alpha^n z + \beta^n,$$

or

$$f(z) = \alpha^n \frac{e^{(1-\varepsilon^n)z}}{1-\varepsilon^n} + \beta^n.$$

Thus $\phi_i^n(z) = \alpha^n \frac{z^{1-\varepsilon^n}}{1-\varepsilon^n} + \beta^n$ for all $z \in \mathbb{R}_+$, where $\varepsilon^n \geq 0$ for function ϕ_i^n to be weakly concave.⁹

By Replication invariance, for any $(u_1, u_2), (v_1, v_2) \in \mathbb{R}_+^2$ we have $(u_1, u_2) \succsim (v_1, v_2) \iff (u_1, u_1, u_2, u_2) \succsim (v_1, v_1, v_2, v_2)$. By the representation obtained for $n = 4$ above, we thus obtain that for any $(u_1, u_2), (v_1, v_2) \in \mathbb{R}_+^2$:

$$(u_1, u_2) \succsim (v_1, v_2) \iff \frac{u_1^{1-\varepsilon}}{1-\varepsilon} + \frac{u_2^{1-\varepsilon}}{1-\varepsilon} \geq \frac{v_1^{1-\varepsilon}}{1-\varepsilon} + \frac{v_2^{1-\varepsilon}}{1-\varepsilon},$$

where $\varepsilon = \varepsilon^4$.

Now consider any $n \in \mathbb{N}$ with $n \geq 3$.¹⁰ By Replication invariance, for any

⁹In the limit case $\varepsilon^n = 1$, we have $\phi_i^n(z) = \ln(z)$ for all $z \in \mathbb{R}_+$.

¹⁰The case $n = 1$ is easily handled by Monotonicity: for all $u_1, v_1 \in \mathbb{R}_+$, $u_1 \succsim v_1 \iff \frac{u_1^{1-\varepsilon}}{1-\varepsilon} \geq \frac{v_1^{1-\varepsilon}}{1-\varepsilon}$ because function ϕ^4 is strictly increasing.

$(u_1, u_2), (v_1, v_2) \in \mathbb{R}_+^2$ we have

$$(u_1, u_2) \succsim (v_1, v_2) \iff \underbrace{(u_1, \dots, u_1)}_{n \text{ times}}, \underbrace{(u_2, \dots, u_2)}_{n \text{ times}} \succsim \underbrace{(v_1, \dots, v_1)}_{n \text{ times}}, \underbrace{(v_2, \dots, v_2)}_{n \text{ times}}$$

so that

$$\frac{u_1^{1-\varepsilon}}{1-\varepsilon} + \frac{u_2^{1-\varepsilon}}{1-\varepsilon} \geq \frac{v_1^{1-\varepsilon}}{1-\varepsilon} + \frac{v_2^{1-\varepsilon}}{1-\varepsilon} \iff \frac{u_1^{1-\varepsilon 2n}}{1-\varepsilon 2n} + \frac{u_2^{1-\varepsilon 2n}}{1-\varepsilon 2n} \geq \frac{v_1^{1-\varepsilon 2n}}{1-\varepsilon 2n} + \frac{v_2^{1-\varepsilon 2n}}{1-\varepsilon 2n}.$$

By the unicity of additive representations up to a positive affine transformation, we must have $\varepsilon^{2n} = \varepsilon$. Now consider any $u, v \in \mathbb{R}_+^n$, and let $\hat{u}, \hat{v} \in \mathbb{R}_+^{2n}$ be such that $m \in \{1, \dots, n\}$ and for all $l \in \{1, 2\}$, $\hat{u}_{2(m-1)+l} = u_m$ and $\hat{v}_{2(m-1)+l} = v_m$. By Replication invariance, $u \succsim v \iff \hat{u} \succsim \hat{v}$, which by the representations we have obtained means that:

$$\sum_{i=1}^n \frac{u_i^{1-\varepsilon^n}}{1-\varepsilon^n} \geq \sum_{i=1}^n \frac{v_i^{1-\varepsilon^n}}{1-\varepsilon^n} \iff \sum_{i=1}^n \frac{u_i^{1-\varepsilon}}{1-\varepsilon} \geq \sum_{i=1}^n \frac{v_i^{1-\varepsilon}}{1-\varepsilon}.$$

By the same argument as above, this implies that $\varepsilon^n = \varepsilon$ for all $n \in \mathbb{N}$. ■

Proposition 1 is about comparisons of vectors with the same size. Let us turn to comparisons of vectors of varying size. To do so, we add four properties on R .

Existence of a critical level. For any $n \in \mathbb{N}$, and for all $u \in \mathbb{R}_+^n$, there exists $z \in \mathbb{R}_+$ such that, if $v \in \mathbb{R}_+^{n+1}$ is defined by $v_i = u_i$ for all $i \in \{1, \dots, n\}$ and $v_{n+1} = z$, then $u \sim v$.

Existence of positive expansion. There exists $z \in \mathbb{R}_+$ such that, for any $n \in \mathbb{N}$, $z \cdot 1_{n+1} \geq z \cdot 1_n$.

We obtain the following result.

Proposition 2 *If a complete quasi-ordering R over $\cup_{n \in \mathbb{N}} \mathbb{R}_+^n$ satisfies Continuity, Monotonicity, Transfer, Symmetry, Existence of a critical level, Existence of positive expansion, Replication invariance and Scale invariance then there exist*

$\varepsilon, \theta \in \mathbb{R}_+$, such that¹¹

$$u R v \iff [n(u)]^\theta \times \left(\frac{1}{n(u)} \sum_{i=1}^{n(u)} u_i^{1-\varepsilon} \right)^{\frac{1}{1-\varepsilon}} \geq [n(v)]^\theta \times \left(\frac{1}{n(v)} \sum_{i=1}^{n(v)} v_i^{1-\varepsilon} \right)^{\frac{1}{1-\varepsilon}}.$$

Proof. By Proposition 1, we know that there exists $\varepsilon \in \mathbb{R}_+$ such that, for all $n \in \mathbb{N}$ and for all $u, v \in \mathbb{R}_+^n$,

$$u R v \iff \left(\frac{1}{n} \sum_{i=1}^n u_i^{1-\varepsilon} \right)^{\frac{1}{1-\varepsilon}} \geq \left(\frac{1}{n} \sum_{i=1}^n v_i^{1-\varepsilon} \right)^{\frac{1}{1-\varepsilon}}.$$

Denote Ξ_n the function $\Xi_n : \mathbb{R}_+^n \rightarrow \mathbb{R}$ defined by $\Xi_n(u) = \left(\frac{1}{n} \sum_{i=1}^n u_i^{1-\varepsilon} \right)^{\frac{1}{1-\varepsilon}}$ for all $u \in \mathbb{R}_+^n$. Function Ξ_n is named a representative utility function (Blackorby, Bossert and Donaldson, 2001).

Consider any $u \in \cup_{n \in \mathbb{N}} \mathbb{R}_+^n$. By repeated applications of Existence of a critical level, for any $k \in \mathbb{N}$, there exists $v \in \mathbb{R}_+^{n(u)+k}$ such that $u \sim v$. By continuity, sets $\{w \in \mathbb{R}_+^{n(u)+k} | v R w\}$ and $\{w \in \mathbb{R}_+^{n(u)+k} | w R v\}$ are closed. But by transitivity, $\{w \in \mathbb{R}_+^{n(u)+k} | v R w\} = \{w \in \mathbb{R}_+^{n(u)+k} | u R w\}$ and $\{w \in \mathbb{R}_+^{n(u)+k} | w R v\} = \{w \in \mathbb{R}_+^{n(u)+k} | w R u\}$. Hence, for any $u \in \cup_{n \in \mathbb{N}} \mathbb{R}_+^n$ and for any $k \in \mathbb{N}$, the sets $\{w \in \mathbb{R}_+^{n(u)+k} | u R w\}$ and $\{w \in \mathbb{R}_+^{n(u)+k} | w R u\}$ are closed. This is the Extended continuity property of Blackorby, Bossert and Donaldson (2001).

By Theorem 1 in Blackorby, Bossert and Donaldson (2001), given that R satisfies Extended continuity and Monotonicity, then there exists a value function $V : \mathbb{N} \times \mathbb{R}_+ \rightarrow \mathbb{R}$, continuous and increasing in its second argument, such that, for all $n, m \in \mathbb{N}$, for all $u \in \mathbb{R}_+^n$, and for all $v \in \mathbb{R}_+^m$,

$$u R v \iff V(n, \Xi_n(u)) \geq V(m, \Xi_m(v)).$$

¹¹For $\varepsilon = 1$, we actually have:

$$u R v \iff [n(u)]^\theta \times \left(\prod_{i=1}^{n(u)} u_i^{\frac{1}{n(u)}} \right) \geq [n(v)]^\theta \times \left(\prod_{i=1}^{n(v)} v_i^{\frac{1}{n(v)}} \right).$$

Without loss of generality, we can normalize V so that $V(1, z) = z$ for all $z \in \mathbb{R}_+$.

By repeated applications of Existence of a critical level, for any $n \in \mathbb{N}$, there exists $u_n \in \mathbb{R}_+^n$ such that $1 \cdot 1_n \sim u_n$, so that $V(1, 1) = V(n, \Xi_n(u_n))$. Let $f : \mathbb{N} \rightarrow \mathbb{R}_+$ be such that $[f(n)]^{-1} = \Xi_n(u_n)$ for each $n \in \mathbb{N}$. We thus have $V(1, 1) = V(n, [f(n)]^{-1})$. Consider any $z \in \mathbb{R}_+$, any $n \in \mathbb{N}$, and denote $\lambda = f(n)x$: by replication invariance $\lambda \cdot 1_n \sim \lambda[f(n)]^{-1} \cdot 1_n$, so that (using the normalization $V(1, y) = y$ for all $y \in \mathbb{R}_+$):

$$f(n)x = \lambda = V(1, \Xi_n(\lambda \cdot 1_n)) = V(n, \Xi_n(\lambda[f(n)]^{-1})) = V(n, x).$$

Hence, for any $z \in \mathbb{R}_+$, and any $n \in \mathbb{N}$, $V(n, z) = f(n)z$.

Consider any $n \in \mathbb{N}$. We know that, $1 \cdot 1_1 \sim [f(n)]^{-1} \cdot 1_n$. Denote $u = 1 \cdot 1_1$ and $v = [f(n)]^{-1} \cdot 1_n$. By Replication Invariance, for any $k \in \mathbb{N}$, $k \star u \sim k \star v$. But $k \star u = 1 \cdot 1_k$ and $k \star v = [f(n)]^{-1} \cdot 1_{nk}$, so that:

$$f(k) = V(k, \Xi_k(1 \cdot 1_k)) = V(nk, \Xi_{nk}([f(n)]^{-1} \cdot 1_{nk})) = \frac{f(nk)}{f(n)}.$$

Therefore, for any $n, k \in \mathbb{N}$, $f(nk) = f(n)f(k)$. Furthermore, by Existence of positive expansion, there exists $z \in \mathbb{R}_+$ such that, for any $n \in \mathbb{N}$, $z \cdot 1_{n+1} \geq z \cdot 1_n$. This implies that $f(n+1)z = V(n+1, \Xi_{n+1}(z \cdot 1_{n+1})) \geq V(n, \Xi_n(z \cdot 1_n)) = f(n)z$. So f is a non-decreasing function $f : \mathbb{N} \rightarrow \mathbb{R}_+$ such that for any $n, k \in \mathbb{N}$, $f(nk) = f(n)f(k)$. By the Theorem in Moser and Lambek (1953), there exists $\theta \in \mathbb{R}_+$ such that $f(n) = n^\theta$. ■

A.1.2 Proof of Theorem 1

Step 1: sure allocations. Assume that the social ordering \succsim satisfies Axiom 2 and Axioms 4–9. Let R^* be the ordering on \mathbb{R}_+^n defined as follows: for any $u, v \in \cup_{n \in \mathbb{N}} \mathbb{R}_+^n$, $u R^* v$ if and only if $(u_1 \cdot 1_T, \dots, u_{n(u)} \cdot 1_T) \succsim (v_1 \cdot 1_T, \dots, v_{n(v)} \cdot 1_T)$. By Assumption 2, R^* is complete preorder over $\cup_{n \in \mathbb{N}} \mathbb{R}_+^n$ that satisfies Continuity.

Because \succsim satisfies Axioms 2 and Axioms 4–9, R^* satisfies Continuity, Monotonicity, Transfer, Symmetry, Existence of a critical level, Existence of positive expansion, Replication invariance and Scale invariance. So, by Proposition 2,

there exist $\varepsilon, \theta \in \mathbb{R}_+$, such that

$$u R^* v \iff [n(u)]^\theta \times \left(\frac{1}{n(u)} \sum_{i=1}^{n(u)} u_i^{1-\varepsilon} \right)^{\frac{1}{1-\varepsilon}} \geq [n(v)]^\theta \times \left(\frac{1}{n(v)} \sum_{i=1}^{n(v)} v_i^{1-\varepsilon} \right)^{\frac{1}{1-\varepsilon}}.$$

By definition of R^* , we thus have that for any $u, v \in \cup_{n \in \mathbb{N}} \mathbb{R}_+^n$,

$$\begin{aligned} & (u_1 \cdot 1_T, \dots, u_{n(u)} \cdot 1_T) \succsim (v_1 \cdot 1_T, \dots, v_{n(v)} \cdot 1_T) \\ \iff & [n(u)]^\theta \times \left(\frac{1}{n(u)} \sum_{i=1}^{n(u)} u_i^{1-\varepsilon} \right)^{\frac{1}{1-\varepsilon}} \geq [n(v)]^\theta \times \left(\frac{1}{n(v)} \sum_{i=1}^{n(v)} v_i^{1-\varepsilon} \right)^{\frac{1}{1-\varepsilon}}. \quad (4) \end{aligned}$$

Step 2: Part 1 of the Theorem. Assume that the social ordering \succsim satisfies Axiom 1 and Axioms 4–9. Clearly Axiom 1 implies Axiom 2 so that the results In Equation (4) holds.

Consider any $\mathbf{p} \in \mathbf{P}$. By definition, $p_i \sim ce(p_i) \cdot 1_T$ for all $i \in \{1, \dots, n(\mathbf{p})\}$, so that, by Axiom 1, $\mathbf{p} \sim (ce_1(p_1) \cdot 1_T, \dots, ce_{n(\mathbf{p})}(p_{n(\mathbf{p})}) \cdot 1_T)$. Therefore, by transitivity of \succsim , for any $\mathbf{p}, \mathbf{p}' \in \mathbf{P}$:

$$\begin{aligned} & \mathbf{p} \succsim \mathbf{p}' \\ \iff & (ce_1(p_1) \cdot 1_T, \dots, ce_{n(\mathbf{p})}(p_{n(\mathbf{p})}) \cdot 1_T) \succsim (ce_1(p'_1) \cdot 1_T, \dots, ce_{n(\mathbf{p}')} (p'_{n(\mathbf{p}')}) \cdot 1_T) \\ \iff & [n(\mathbf{p})]^\theta \times \left(\frac{1}{n(\mathbf{p})} \sum_{i=1}^{n(\mathbf{p})} (ce_i(p_i))^{1-\varepsilon} \right)^{\frac{1}{1-\varepsilon}} \geq [n(\mathbf{p}')]^\theta \times \left(\frac{1}{n(\mathbf{p}')} \sum_{i=1}^{n(\mathbf{p}')} (ce_i(p'_i))^{1-\varepsilon} \right)^{\frac{1}{1-\varepsilon}}. \end{aligned}$$

Step 2: Part 2 of the Theorem. Assume that the social ordering \succsim satisfies Axioms 2–9, so that the results In Equation (4) holds.

Consider any $\mathbf{c} \in \mathbf{C}$. By definition, $c_i \sim e(c_i) \cdot 1_T$ for all $i \in \{1, \dots, n(\mathbf{c})\}$, so that, by Axiom 2, $\mathbf{c} \sim (e_1(c_1) \cdot 1_T, \dots, e_{n(\mathbf{c})}(c_{n(\mathbf{c})}) \cdot 1_T)$. Therefore, by transitivity

of \succsim , for any $\mathbf{c}, \mathbf{c}' \in \mathbf{C}$:

$$\begin{aligned} & \mathbf{c} \succsim \mathbf{c}' \\ \iff & (e_1(c_1) \cdot 1_T, \dots, e_{n(\mathbf{c})}(c_{n(\mathbf{c})}) \cdot 1_T) \succsim (e_1(c'_1) \cdot 1_T, \dots, e_{n(\mathbf{c}')}(\hat{c}'_{n(\mathbf{c}')}) \cdot 1_T) \\ \iff & [n(\mathbf{c})]^\theta \times \left(\frac{1}{n(\mathbf{c})} \sum_{i=1}^{n(\mathbf{c})} [e_i(c_i)]^{1-\varepsilon} \right)^{\frac{1}{1-\varepsilon}} \geq [n(\mathbf{c}')]^\theta \times \left(\frac{1}{n(\mathbf{c}')} \sum_{i=1}^{n(\mathbf{c}')} [e_i(c'_i)]^{1-\varepsilon} \right)^{\frac{1}{1-\varepsilon}}. \end{aligned}$$

But, because \succsim satisfies Axioms 3, there exists $U : \mathbf{C} \rightarrow \mathbb{R}$ such that, for any $\mathbf{c}, \mathbf{c}' \in \mathbf{C}$, $\mathbf{c} \succsim \mathbf{c}'$ if and only if $U(\mathbf{c}) \geq U(\mathbf{c}')$. Gathering the results, there must exist a continuous and increasing function $\Psi : \mathbb{R} \rightarrow \mathbb{R}$. such that

$$U(\mathbf{c}) = \Psi \left[[n(\mathbf{c})]^\theta \times \left(\frac{1}{n(\mathbf{c})} \sum_{i=1}^{n(\mathbf{c})} (e_i(c_i))^{1-\varepsilon} \right)^{\frac{1}{1-\varepsilon}} \right].$$

Because \succsim satisfies Axioms 3, for all $\mathbf{p}, \mathbf{q} \in \mathbf{P}$:

$$\mathbf{p} \succsim \mathbf{q} \iff \sum_{\mathbf{c} \in \mathbf{C}} \mathbf{p}(\mathbf{c}) U(\mathbf{c}) \geq \sum_{\mathbf{c} \in \mathbf{C}} \mathbf{q}(\mathbf{c}) U(\mathbf{c}).$$

A.2 A RICE model with endogenous population

A.2.1 A modified RICE model

Integrated assessment models of climate and the economy are used to inform climate policy. We create a variant of the Regional Integrated model of Climate and the Economy (RICE) – a regionally disaggregated version of the Dynamic Integrated model of Climate and the Economy (DICE) – in which population dynamics are partly endogenous.¹²

Like other IAMs, our model combines a simple representation of the economy

¹²RICE2010 was developed by William Nordhaus (see Nordhaus, 2010, for a presentation of the model). It is based on the widely used DICE model, also developed by William Nordhaus. A comprehensive description of the most recent version of the DICE model is available at the address: <https://sites.google.com/site/williamdnordhaus/dice-rice>.

and a climate module. The economic module is a Solow-like growth model with capital accumulation. This module also includes climate mitigation costs and a climate damage function, that takes into account the monetary impacts (and some non-monetary impacts) of climate change. Another key parameter is exogenous technical progress (TFP growth), which declines through time and partially converges across regions.

The climate module describes the evolution of the global temperature increase and radiative forcing, taking the emissions, that depend on the abatement level, as an input. In RICE, the temperature increase feeds back on the economy through the damage function. In our model, the temperature increase also feeds back through the mortality rate.

Our model is a simulation model derived from Norhaus's RICE2010 model and is coded in Python.¹³ The main difference is that we have introduced endogenous population dynamics in the model. To do so, the version used in this paper only involves 6 regions (as opposed to the 12 regions in the initial RICE model): Africa, Asia, Europe, Latin America, Northern America and Oceania. This was done to match regions in Hales et al. (2014) and data from the UN World Population Prospects (WPP). We recalibrated the RICE model accordingly.

Introducing climate change-related mortality implies that mortality patterns depend on climate conditions. Moreover mortality patterns change differently in different age groups and different regions. As a consequence, the whole structure of the population will change with climate conditions, and it is necessary to keep track of those changes. We account for endogenous population dynamics following the methodology used in Pottier et al. (2019) in an aggregate model similar to the DICE model. The main difference here is that we represent regional population dynamics in 6 regions.¹⁴

Our baseline population dynamics are based on the cohort-component method,

¹³A version of the NICE model in Julia, on which our model is based, is available at: <https://github.com/anthofflab/MimiRICE2010.jl>.

¹⁴For a more detailed presentation on how population dynamics is endogenized, see Pottier et al. (2019)

which is the commonly used method to project population in the long run. We rely on the description of this method by Preston et al. (2001) and we aim at reproducing, in the baseline, the projections of the UN WPP.

To endogenize population size, we assume that the baseline dynamics will adjust depending on global average temperature. More specifically, we take fertility rates and migrations as given by the baseline dynamics but we assume that mortality rates change depending on temperature. Without climate change-related mortality, life-tables at time t are computed from a region-, age- and sex- specific probability of dying $q_a^{rs}(t)$ (where r is the index for the region, s is the index for sex, a the index for the age group, and t the index for the time period). With climate change-related mortality, we make the assumption that the probability of dying becomes:

$$\tilde{q}_a^{rs}(t) = q_a^{rs}(t) \times \left[1 + \alpha_a^r \cdot T(t) \right]$$

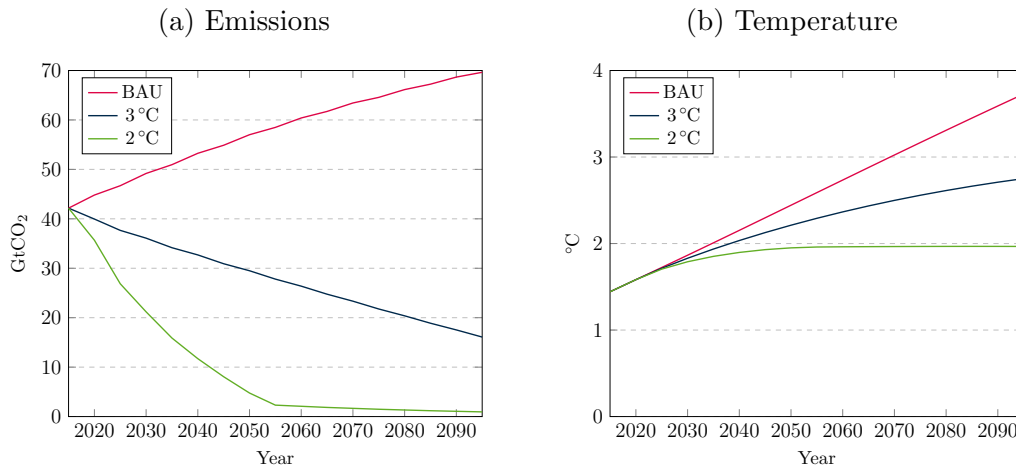
where T_t is the global temperature increase and α_a^r is the relative increase in the probability of dying due at age a in region r at some reference temperature. Calibration of the α_a^r coefficients is based on the data in Hales et al. (2014).

A.2.2 Scenarios

IAMs are typically used to compute optimal policies according to a specific social welfare criterion. In this paper, we instead study different scenarios to evaluate in each scenario the distribution of climate impacts between standard consumption impacts, mortality impacts, inequality impacts and total population loss. We also compare these scenarios to see how including other impacts may change the balance in favor of a specific policy.

We consider three climate policy scenarios that are related to three different emission trajectories. In the BAU scenario, there is no control of GHG emissions: the GHG stock builds up rapidly in the atmosphere and climate change is substantial. The 2°C and 3°C scenarios correspond to two stabilisation policies that control GHG emissions so as to stabilize global temperature increase. Emissions and temperature in these scenarios are represented in Figure 3.

Figure 3: Three scenarios: BAU, 3 °C and 2 °C



These scenarios have different consequences in terms of mortality and total population size, as shown in Figure 4.

Regarding mortality, climate change (from the reference situations, which is pre-industrial temperature) induces many years of life lost. Panel (a) in Figure 4 indicates these years of life lost (which is a standard measure in demography to assess additional mortality related to a cause) in our three scenarios. First, remark that the impact is already large in 2020:¹⁵ this is due to the many extra deaths already occurring due to undernutrition, malaria, diarrheal diseases and heat. Second, the number of years of life lost has a different pattern depending on the scenario: it is slightly increasing then quite stable in the BAU, decreasing after a few years in the 2 °C and 3 °C scenarios. Remark that temperature increases even in the 2 °C scenario, so that we could expect that more years of life be lost in the future. This is actually not the case, thanks to improved underlying health conditions in the future that reduce the effect of climate change on mortality.¹⁶

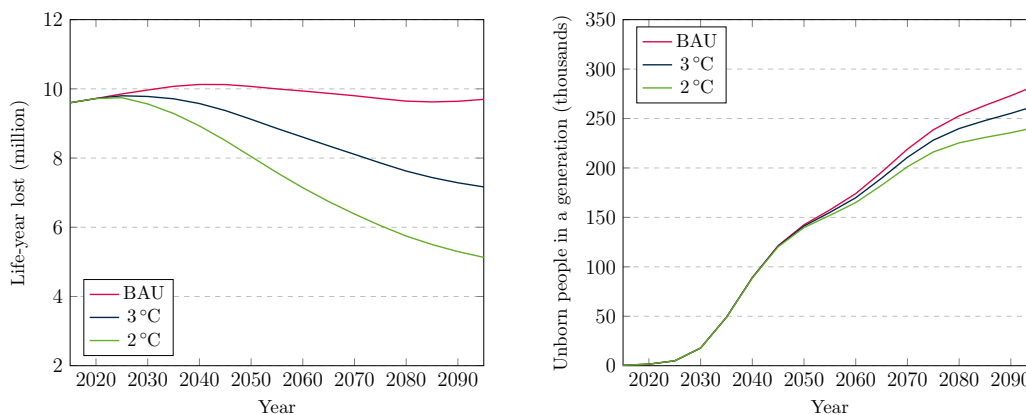
Regarding total population in a generation, Panel (b) in Figure 4 indicates

¹⁵At the date this paper is written, the current COVID-19 pandemic has taken approximately 5 million life years.

¹⁶Indeed, the additional climate related risk is proportionality to baseline mortality risk in our specification. See Pottier et al. (2019) for a more detailed analysis.

Figure 4: The effects of climate change on population

(a) Number of years of life lost due to climate change (b) Number of people not born in a generation because of climate change



the number of a people who are not born because of the climate related risk on mortality. This happens because when people die earlier than expected they may not be able to have children (provided they died before the reproduction age). Hence there are “missing” future people because of climate change. This effect is cumulative through time because these unborn people may themselves have had children etc. Note that our model does not account for endogenous fertility, and in particular there is no replacement natality in the model. Replacement natality may temper the above-mentioned effect. We can see that the magnitude of the total population size effect is quite similar in the three scenarios, except at the end of the century.

A.3 Additional results

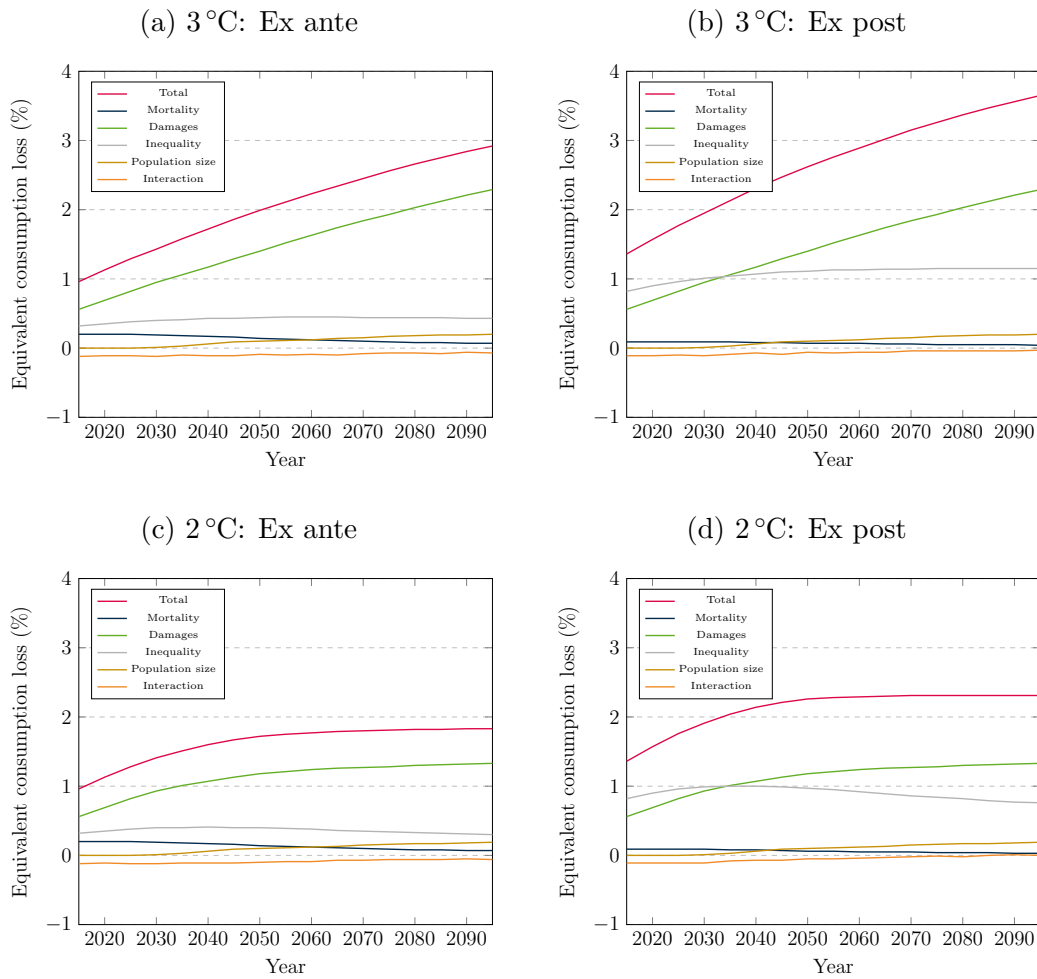
A.3.1 Results for losses in the 3°C and 2°C scenarios

Figure 5 shows the welfare losses due to total population loss, standard climate damages, mortality and inequality in the 3°C and 2°C scenarios.

Panel (a) of Figure 5 shows losses for the ex ante approach in the 3°C scenario, panel (b) of the figure shows losses for the ex post approach in the 3°C scenario,

panel (c) of the figure shows losses for the ex ante approach in the 2 °C scenario, and panel (d) of the figure shows losses for the ex post approach in the 2 °C scenario.

Figure 5: Equivalent welfare loss from climate change in the 3 °C and 2 °C scenarios



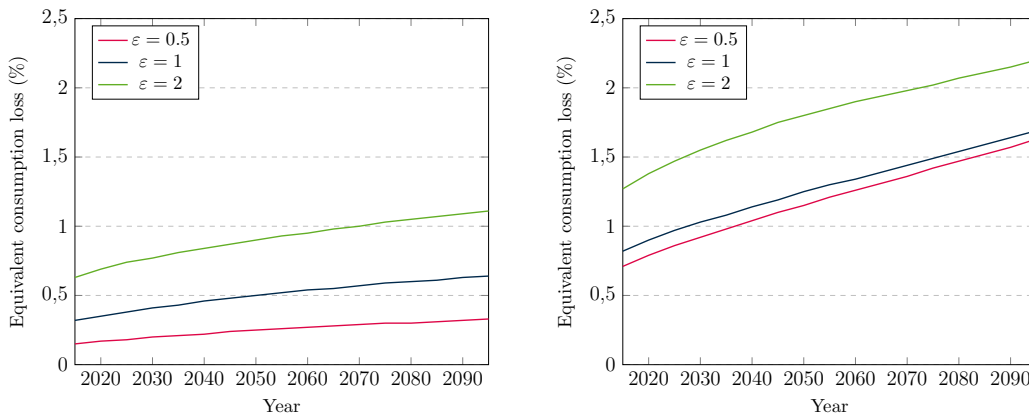
A.3.2 Sensitivity analysis

Figure 6 presents the sensitivity of our analysis in Section 3.2.1 to changes in parameters ε and θ .

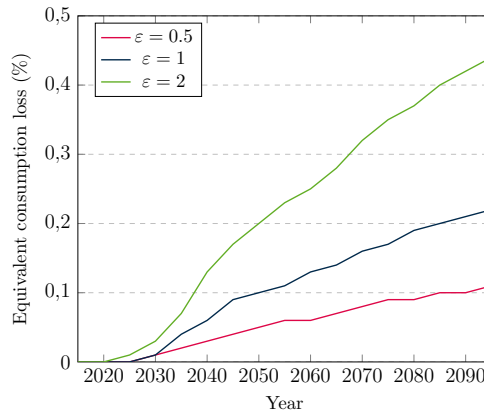
Panel (a) of Figure A.3.1 shows how the welfare loss related to inequality depends on ε in the ex ante approach. Unsurprisingly, increasing ε increases this loss related to inequality.

Figure 6: Sensitivity analysis: Impacts in the BAU

(a) Welfare effect of inequality: Ex ante (b) Welfare effect of inequality: Ex post



(c) Welfare effect of population size



Panel (b) of Figure A.3.1 shows how the welfare loss related to inequality depends on ε in the ex post approach. The results are similar to those in the ex

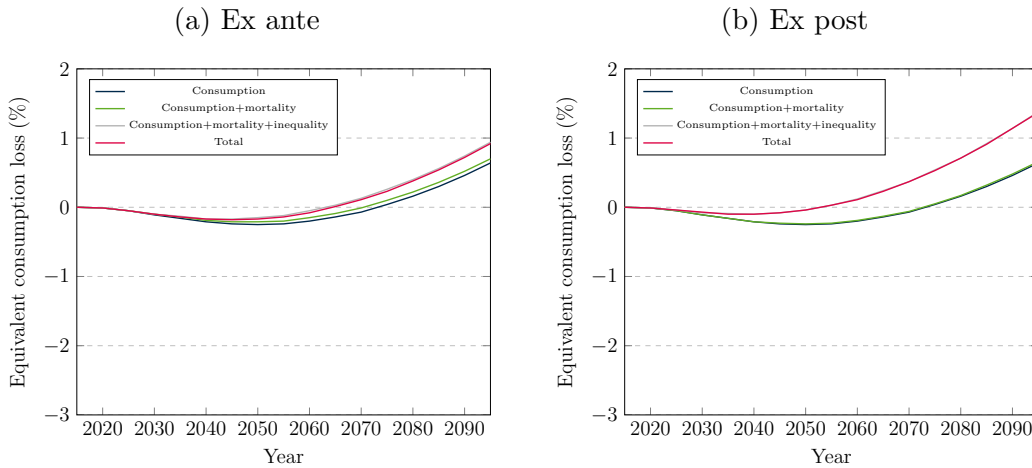
ante approach. But here we see that substantial losses can be obtained for high (but not unreasonably high) values of ε , for instance $\varepsilon = 2$. In that case, the loss at the end of the period is about 2.2% of consumption per capita.

Panel (c) of Figure A.3.1 shows how the welfare loss related to total population size depends on θ . Note that, by the decomposition formulas in Section 3.2.1, this loss is the same in the ex ante and the ex post approach. Again, we obtain that the loss is increasing in θ , although it is never very large. We have not displayed the case $\theta = 0$ (average case) where the loss would by definition always be equal to 0.

A.3.3 Comparing the 3°C policy to the BAU

Figure 7 displays the equivalent welfare gains / losses in a 3°C policy scenarios compared to the BAU.

Figure 7: Equivalent welfare gains / losses from a 3°C policy



Like in the 2°C policy scenario, the 3°C policy is costly in terms of per capita consumption for the first generations (until 2075). The cost is much lower than the one of the 2°C policy (the maximum is cost 0.25% of consumption per capita in 2050). Including mortality has a small effect but including inequality has a

larger effect, especially in the ex post case. In total, including non consumption effects, the losses are limited (0.18% of consumption per capita in the ex ante case; 0.1% in the ex post case). And gains can occur early on (in 2065 in the ex ante case, in 2055 in the ex post case).