Generous Sustainability

Reyer Gerlagh*

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Abstract

I define "*generous sustainability*" as a combination of two conditions: neither instantaneous maximin income nor attainable maximin income should decrease over time. I provide a formal definition and study applications to a Climate Economy with bounded and with unbounded growth. Generosity is shown to require that GHG emissions are limited to levels that do not cause irreversible system damages if some group of people systematically value these systems.

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*Gerlagh <r.gerlagh@uvt.nl> is at the Economics Department and Tilburg Sustainability Center of Tilburg University (Warandelaan 2, 5037AB Tilburg), and a CESifo research network fellow. This version is an update of CESifo WP 5092. An up-to-date webversion is available through https://surfdrive.surf.nl/files/public.php?service=files&t=9f6047aaf96c76d0baea386d3ca8a345. I want to thank Geir Asheim, Jack Pezzey, Marc Fleurbay, Paolo Piacquadio,Thomas Sterner and Vincent Martinet for comments. The usual disclaimer applies.

1 Introduction

"We deserve to do more than just survive; we deserve to thrive." (Kathy Jetnil-Kijiner[1])

"progress without destruction is possible" (Chico Mendes[2])

Avoiding regress, or even disaster, is a core element of various concepts of sustainability in the literature, but it is not enough. This paper presents a concept of sustainability that gives more weight to the best possible future, evaluating current actions by their consequences for that potential future.

In economic theory, sustainability is defined and measured in very different ways (Fleurbaey 2013). One approach formalizes sustainability (or more precisely "sustainedness") as an ex-post condition on the utility sequence, for example as in the requirement that generations' utility should be non-decreasing with time (Pezzey 1997). A second line of analysis frames sustainability in terms of the (intergenerational) welfare function that society should maximize when allocating its resources over time. Chichilnisky (1996, 1997) interpreted sustainability as a non-zero weight given to the interests of the very-far future generations. Zuber and Asheim (2012) present a utilitarian perspective on sustainaibility, requiring the weights given to generations in intergenerational allocation choices to decrease with increasing generation's utility levels. Llavador et al. (2011) maximize the utility level that is consistent with a pre-determined constant growth rate of utility. A third approach to sustainability formalizes the concept as 'something that must be conserved for the very long run' (Solow 1993). Martinet (2011) and Cairns and Martinet (2014) define sustainability as non-decreasing maximin income (defined in detail below). The advantage of the last approach is that sustainability defined this way can be ascertained without making a precise prediction about the future generations' decisions, since only their possibility set matters (Fleurbaey 2013).

Though the approaches differ fundamentally by use of their method, many of them share two features: a focus on the past as the benchmark, and a concern for lower bounds. Sustainability aims to protect the weak and poor from further deprivation, both in the present and the future. The focus is explicit in the well-known definition of sustainability

[1]A poem to my Daughter, Kathy Jetnil-Kijiner addressing the United Nations Climate Summit Opening Ceremony, 24 September 2014, New York. The poem speaks of the future of the people living on small islands.

[2]Chico Mendes was a rubber tapper in the Amazon and a campaigner for the sustainable exploitation of the rain forests. The quote is part of the closing lines of a speech at 6th December 1988, in Sao Pablo. Chico Mendes was born 1944 and died 22nd December 1988, shot by the son of a local rancher.

given by the World Commission on Environment and Development, as development "that meets the needs of the present, without compromising the ability of future generations to meet their own needs" (WCED 1987).[3] In contrast, Jetnil-Kijiner calls the United Nations Summit to provide her child with the possibility to thrive. The request marks an important deviation from a minimalistic sustainability concept. She calls society for a positive contribution to the development of the future prospect (Gerlagh and Sterner 2013). While it is essential to protect the future against poverty and to ensure that the future can meet its basic needs, and avoiding small risks of total disaster is very important, it is not enough. Most integrated assessment models and many observers believe we have the potential to achieve a bright future for society with many decades, possibly centuries, of growth.[4] This harbours the potential for eradication of poverty and of a future where people on average enjoy a better life than today. This is the bright future we stand to (partly) lose with climate change. In such a context, it is overly conservative to limit the content of the term "sustainability" to meaning "no worse than today" (Llavador et al. 2011).

The last century has shown a world with a robust and steady per capita income growth of about 2 per cent per year. We see developing countries rapidly catching up, *and* the high-income countries continuing their progress. Whereas the developing countries gain from institutional changes, the frontier economies gain from continued progress of technology and knowledge; there is no end in sight to human ingenuity. We can do better in the future as compared to the past: to eradicate poverty, improve education worldwide, bring more equal chances for all world citizen including closing the gender gap, and make a better place. In this essay I make a small step to interpret the call for contributing to a better future in a formal framework. I will define a perspective labeled generous sustainability or generosity, which requires that we preserve two opportunities: to conserve the utility level that can be sustained forever, but also to preserve the best achievable world, that is, generosity protects the maximal potential of future generations to thrive.

Yet, we also need to confront the optimist future view with history, which shows the side effects of worldwide economic progress (Victor, Gerlagh and Baiocchi 2014). The economic successes of the rapidly emerging countries, the new world middle class, are

[3] Chichilnisky's sustainable welfare function (1996, 1997) is the outlier, giving positive weight to the far-future welfare, independent of the past or of any constraints on utility.

[4] Neumayer (1999, Section 3.2 & 3.4) and Pezzey and Burke (2014) point out that such beliefs remain beliefs, in that they cannot be usefully falsified.

accompanied by an unprecedented rise in resource use and greenhouse gas emissions. We need to develop a concept of sustainability that supports economic progress, while at the same time, sustainability has to take serious the protection of the scarce environmental resources. Generosity is more demanding relative to comparable concepts that require the maintenance of opportunity (Martinet 2011, Fleurbaey 2013, Cairns and Martinet 2014), but it is not too demanding. It does not require huge savings to increase wealth of a future generation that is richer than the present, as zero-discounting does (Nordhaus 1997).[5] Generosity is also less demanding than Llavador et al. (2011), who impose an exogenous constant growth rate of utility. The core concept of generosity is the preservation of resources that are essential to future utility. Chico Mendes, cited above, captures the idea through a remarkably modest statement, which we will formalize below.

Before going into the formal analysis, an illustrative example may clarify the core of the concept and conclusions of this paper. Assume that a country's income can grow by a factor five in hundred years time. Furthermore, assume that the country has large forest areas that can profitably be harvested, offering substantial economic gain over the first decades. But cutting the forests also irreversibly destroys part of the supporting ecosystems, and all future generations after some time, say after 2050, will regret. What are the principles that govern the social (il)legitimacy for cutting the forests? The typical sustainability do not consider the loss of the forests as problematic, unless the regret for biodiversity loss exceeds the benefits from income growth, that is, unless utility actually declines. Azar and Schneider (2002) sketch a similar dilemma for climate change, showing that in most models the cost of climate protection is equivalent to one year of economic growth, while damages may be irreversible. Yet, classic sustainability paradigms consider 'small' costs and irreversible damages as insufficient conditions for conservation; they demand nature's preservation only if there is a potential catastrophe, or if the lost environmental resources are non-substitutable (cf. Neumayer 2007).[6] Generosity sets out some principles that may provide guidelines; it asks whether there is a future where citizen, whose income in the very long run has continued to increase, consider themselves uncompensatably worse off without the forests and climate conservation as compared to the situtION with conservation. If an action irreversibly deteriorates the prospects of a

[5] See Gerlagh and Liski (2012) for a discussion of the connection between capital savings and climate policy.

[6] Note that Azar and Schneider (2002) also provide no principles that can be used to convert the observation of low abatement costs and irreversible damages into an argument for climate conservation (Gerlagh and Papyrakis 2003).

stream of future citizens without bounds, while there is no other group of future citizen whose prospects are permanently improved by that action, then that action conflicts with generosity.[7] Restated, if progress is possible without the irreversible destruction of some resources, and if these resources are uncompensatably valued by some group of people in each period (defined precisely in the subsequent sections), generosity stipulates that progress with conservation is always preferred over progresss complemented by destruction, also if the latter leads to faster income growth.

In the next section I shortly define generosity formally and as succinctly as possible. Yet the main aim of this manuscript is not to lay down a strict formal analysis, but to broaden our conceptual perception of a sustainable future and its practical conditions in, for example, the climate change debate. Therefore, the subsequent section applies the concept to a simple climate-economy model without and with unbounded growth. I then briefly discuss a natural extension of generosity to the context of uncertainty and intra-generational inequality. The last section discusses the context-dependence of sustainability, specifically I discuss the context under which generosity is more, or less, relevant as principle.

2 Generosity

To set the stage, we use a simple set up. We consider state variables x_t, and utility u_t. Time is discrete, starting at $t = 1$. An action is a choice $(x_t, x_{t+1}) \in \Gamma$ where Γ is convex and supports stationarity: for all $x_t : (x_t, x_t) \in \Gamma$. Actions result in utility $u_t = u(x_t, x_{t+1})$, with $u(.)$ continous and concave. Generosity is defined as a constraint on the actions (x_t, x_{t+1}). We do not consider welfare optimization over the sequence u_t; generosity has a different basis vis-a-vis (zero-)discounted utility, non-dictatorship of the present, and rank-discounted utility. It is also incomparable to concepts such as non-decreasing utility, as it does not evaluate ex-post outcomes, but current actions.

At time t, the generation inherits the economy x_t and it has to decide on its action (x_t, x_{t+1}). We denote by ${}_tu = (u_t, u_{t+1}, ...)$ a vector of utility starting at period t, and by ${}_tU = U(x_t)$ the set of feasible utility sequences. Generosity preserves two opportunties defined in terms of welfare. The first opportunity measures Hicksian or 'maximin' income.

[7] The term irreversible should not be taken literally as in mathematics; it's meaning is constrained by our imagination of a meaningful period. Similarly, in the formal analysis, we let the index for time and generations run to infinity. It is clear that, over billion of years, all changes that the current generation makes will wash out.

Definition 1 *Given the current state x_t, Hicksian income is the supremum of the infemum utility level*

$$\mathcal{H}(x_t) = \sup_{{}_t u \in U(x_t)} \left\{ \inf_{\tau} \{u_\tau\} \right\} \tag{1}$$

Since the action set is convex, and utility concave, it follows immediately that Hicksian income is a concave function, and thus continuous on the interior of the support for x_t.

The second opportunity meausures utility in the best achievable stationary world. It is defined recursively, on the basis of Hicksian income. We could loosely call it 'maximaximin' or 'maximax' utility:

Definition 2 *Given the current state x_t, Attainable income is the supremum of Hicksian income that can be reached*

$$\mathcal{A}(x_t) = \sup_{\tau > t} \{\mathcal{H}(x_\tau) | x_\tau \text{ attainable from } x_t\} \tag{2}$$

where x_τ attainable from x_t means that we consider all feasible paths $(x_t, x_{t+1}, ...)$ starting at t.

Similar to Hicksian income, Attainable income is concave and continuous on the interior of the support for x_t.

We define an action (x_t, x_{t+1}) to be generous if it keeps the two opportunities intact. First, it must not decrease Hicksian income, as in Cairns and Martinet (2014), who call the increase in Hicksian income sustainable savings (different from genuine savings). The second condition distinguishes generosity from the previous definitions of sustainability, and it is much more demanding, as we will see in our applications below.

Definition 3 *An action $(x_t, x_{t+1}) \in \Gamma$ is Generous if and only if*

$$\mathcal{H}(x_t) \leq \mathcal{H}(x_{t+1}) \text{ and } \mathcal{A}(x_t) = \mathcal{A}(x_{t+1}) \tag{3}$$

Notice that attainable income cannot increase over time; it can only remain constant or decrease. There cannot be positive attainable savings, though we can loosely speak of the 'attainable deficit' when attainable income decreases. For future reference, we refer to these constraints as the first and second generosity constraint.

The attainable deficit somewhat resembles an idea explored in Pezzey and Burke (2014), who calculate an artificial measure of genuine (adjusted net) savings when temperature change is not allowed to exceed a specific treshold. But where Pezzey and Burke need to assume very pessimistic climate and damage dynamics, the attainable deficit measures the gap between a bright and a brigher future. Moreover, the concept of attainable deficit is based on rigourous analytics broadly applicable.

Generosity requires non-negative sustainable savings, and the absence of an attainable deficit. We are now in a position to illustrate generosity by use of illustrative economies.

3 Climate-Economy Models

The purpose of the models below is to illustrate the relevance of generosity for climate change policies. As generosity imposes two conditions, it requires at least two state variables to be effective. Generosity is not restrictive in a simple AK growth economy, and does not add much insight for a one-capital stock Ramsey economy, but it has clear consequences for a climate change economy. The two examples below show that the consequences depend on the perspective of bounded or unbounded economic growth, and depend on the assumed substitutability (see Neumayer 1992 for a discussion).

3.1 Space-ship earth

Let us consider a stylized climate-economy model, with economic growth. The first model assumes a bound to economic long-run output so that constant perpetual growth, as imposed by Llavador et al. (2011) in the context of climate change, is infeasible for the climate-economy studied in this section. Generosity is more flexible, but still requires tight emission constraints, as we will see below. Technology in our economy is described through

$$u_t = u(c_t) \tag{4}$$

$$c_t + k_{t+1} = A_t \sigma(a_t) \Omega(m_t) f(k_t/A_t) \tag{5}$$

$$\mathbf{s}_{t+1} = \mathbf{B}\mathbf{s}_t + (1 - a_t)\mathbf{b}k_t \tag{6}$$

$$m_{t+1} = h(m_t, \mathbf{s}_t) \tag{7}$$

where A_t is a measure of labour productivity, a_t is abatement effort in relative terms ($a_t = 1$ means zero emissions), $\sigma(a_t)$ is a measure for the cost of abatement in terms of reduced output, $\Omega(m_t)$ is the relative costs of climate change, dependent on m_t, which is the state of the climate affecting output, e.g. a measure of global temperature change, and $\mathbf{s}_t$ is a vector of CO2 reservoirs in excess of the natural level, such as the atmosphere and ocean layers, $\mathbf{B}$ describes the diffusion between reservoirs, and $\mathbf{b}$ is a vector which elements sum to one describing the immediate distribution of emissions over the reservoirs. We normalize the functions such that $\sigma(0) = \Omega(0) = 1$, $\sigma' < 0$, $\Omega' < 0$, $\sigma(1) > 0$, $\Omega > 0$, $\mathbf{B} \geq 0$, $\mathbf{b} \geq \mathbf{0}$, $h(0,0) = 0$, $0 < h_m < 1$, $0 < h_s$. The capital stock and CO2 stocks are normalized such that, if there is no abatement, one unit of capital emits one unit of CO2.

The climate-economy model abstracts from resource exhaustion concerns, and focuses on the environmental degradation concern.[8] We assume that part of climate change is irreversible: CO2 cannot leave the system, in technical terms, the columns of $\mathbf{B}$ sum to the unit vector $\mathbf{B}\overrightarrow{\mathbf{1}}=\overrightarrow{\mathbf{1}}$, where $\overrightarrow{\mathbf{1}}=(1,1,...,1)$.[9] We assume that the climate system is dynamically stable with persistent effects, and $\lim_{t\to\infty}\mathbf{B}^t \gg 0$ is well-defined with strictly positive elements, equal rows up to scaling so that for the long-run consequences only cumulative emissions matter:

$$\mathbf{s}^* = \lim_{t\to\infty}\mathbf{B}^t\mathbf{s}_1 = \overrightarrow{\mathbf{s}}\,\overrightarrow{\mathbf{1}}'\mathbf{s}_1 \tag{8}$$

where $\overrightarrow{\mathbf{s}} > 0$ with elements that sum to one ($\overrightarrow{\mathbf{1}}'\overrightarrow{\mathbf{s}} = 1$) is the long-term equilibrium relative distribution of CO2 over the reservoirs, and $\mathbf{u}$ sums CO2 stocks over the reservoirs in $\mathbf{s}_1$, so that $r_1 = \overrightarrow{\mathbf{1}}'\mathbf{s}_1$ measures cumulative historic emissions, and future cumulative emissions are given by

$$r_{t+1} = r_t + (1 - a_t)k_t. \tag{9}$$

Cumulative emissions are non-decreasing, so that the limit is well-defined:

$$r_\infty = \lim_{t\to\infty} r_t \tag{10}$$

We can then define the implicit function of long-term consequences of current cumulative emissions, $m^*(r_t)$, by

$$m^*(r_t) = h(m^*(\overrightarrow{\mathbf{s}}r_t), \overrightarrow{\mathbf{s}}r_t) \tag{11}$$

and assume that this function is well defined, and $m^{*\prime}(.) \equiv \overrightarrow{\mathbf{s}}'\partial m^*(\overrightarrow{\mathbf{s}}r_t)/\partial(\overrightarrow{\mathbf{s}}r_t) > 0$. Long-term consequences of current emissions may become small but will never completely vanish.

Zero-discounted utilitarianism ensures the resource conservation property of the model, but also leads to unrealistic and undesirable high savings rate (Nordhaus 1997). Non-decreasing utility and rank-discounted utility do not alter the outcome for this economy,

[8] Read Neumayer (1992, Section 3.2 and 3.3) for a clear separation between resource exhaustion and environmental degradation as two major sustainability concerns, and an elaborate discussion of various positions found in the literature.

[9] Our modelling of the carbon reservoirs-climate change dynamics relates to the "trillionth-ton" literature on a limit to cumulative CO2 emissions, see e.g. Allen et al. 2009.

unless climate damages are sufficiently strong (a decrease in $\Omega(m_t)$) so that they more than offsets the increase in technology A_t. Though such damages are not ruled out by the model set up, most numerically applied studies on climate change do not find such damages (Gerlagh and Papyrakis 2003). Chichilnisky's welfare function provides some justification for reduced emissions, but its policy is time inconsistent.

The economy has too many parts to derive a general analytical solution for maximin income. We can derive an expression for attainable income under suitable assumptions, though. We first consider the perspective of 'spaceship earth', where output is bound by finite resources. Formally, we assume that A_t is increasing and converging to some level, $A_t \to A^*$. We can then calculate the bliss steady state, dependent on the current history of CO2 emitted:

$$k^*(r_t) = \arg\max_k \{A^*\sigma(1)\Omega(m^*(r_t))f(k) - k\} \tag{12}$$

$$c^*(r_t) = A^*\sigma(1)\Omega(m^*(r_t))f(k^*) - k^* \tag{13}$$

Attainable income, for $k_t > 0$, is now immediately determined as

$$\mathcal{A}(k_t, r_t, m_t) = c^*(r_t) \tag{14}$$

We immediately see that, as $c^{*\prime}(.) < 0$, generosity implies a stop to the build up of emissions. We state this result as proposition:

Proposition 1 *Under non-negative emissions, $a_t \leq 1$, and the 'finite earth' assumption of $A_t \to A^*$ and a closed CO2 system (8), generosity requires full abatement, $a_t = 1$.*

Note that the DICE model (Nordhaus 2008) satisfies the above conditions, so that the proposition implies a zero-emissions policy in DICE. The above discussion naturally leads to the question of future carbon capture and sequestration, allowing $a_t > 1$, as such may reverse part of past emissions. If negative emissions are feasible, attainable income is independent of historic emisisons:

$$k^* = \arg\max_k \{A^*\sigma(1)\Omega(0)f(k) - k\} \tag{15}$$

$$c^* = A^*\sigma(1)\Omega(0)f(k^*) - k^* \tag{16}$$

Indeed, under this condition, generosity does not necessarily constrain current emissions, if all consequences are reversable, e.g. through carbon capture and sequestration.

But, generosity has a substantial effect on optimal climate policy, nonetheless, as it indirectly changes the conditions for optimal climate policy. Whereas a standard cost-benefit analysis compares the marginal costs of abatement to the net present value of marginal damages, an efficient generous policy compares the marginal costs of abatement with the net present value of future marginal costs to capture and storage, assuming that no irreversible damages occur in between the release and capture of atmospheric CO2. Having written A_t as labour productivity, we can use it as a proxy for income and emissions without abatement and derive a rule of thumb for generosity:

Remark 1 *Under the 'finite earth' assumption of $A_t \to A^*$ and (8), when negative emissions, $a_t > 1$ are possible, a rule of thumb necessary condition for generosity is that any below-full abatement, $a_t < 1$, is matched by a future above-full abatement $a_\tau > 1$ that leaves future income above current income:*

$$A_t \Omega_t \sigma(a_t) < -A_\tau \Omega_\tau \sigma(a_\tau) \text{ and } (1 - a_t) A_t \Omega_t = (a_\tau - 1) A_\tau \Omega_\tau \tag{17}$$

Effectively, fossil fuel combustion is seen as debt to the future, admissable if it is part of a development process and if it can be 'repaired' in the future and if future income is sufficient to pay for the repair costs. The rule of thumb combines the requirement for maximin income and Attainable income. Note that the repair does not need to take place, but it must be feasible. The future generations themselves can decide whether and when they engage in negative emissions.

3.2 A climate-economy model without bounds

We now consider the optimist perspective of perpetual growth, $A_t \to \infty$, $f'(0) = \infty$. The immediate consequence is that output can grow without bound, irrespective of climate change: $\mathcal{A}(k_t, \mathbf{s}_t, m_t) = u(\infty)$, as in the AK model.[10] The interpretation of unbounded growth is that adding value is not restricted to physical consumption, combined with the insight that modern services and industrial production can create its own artificial environment if needed and thus is not very dependent on climate conditions. Many applied climate-economy models foresee no need for a drop in future consumption as a consequence of current emissions, so that maximin income is also not decreasing, and thus under such optimistic assumptions, generosity may not require tough climate policies.

[10] Note that we do not impose a lower bound on the long-run growth rate, so that the constant growth requirement by Llavador et al. (2011) could still be infeasible.

The above model, where all damages occur in terms of consumption goods, puts a weak bound on emissions.

Proposition 2 *Under non-negative emissions, $a_t \leq 1$, and 'unbounded growth', $A_t \rightarrow \infty$, $f'(0) = \infty$ and a closed CO2 system (8), generosity, by maintaining Attainable income, requires prevention of a full catastrophe. Cumulative emissions must remain below a threshold*

$$r_t < r^*$$

that satisfies

$$\Omega(m^*(r^*)) = 0 \tag{18}$$

If emissions can become negative, the same conditions as for finite earth apply, but only after the climate deteriorates beyond the threshold of cumulative emissions r^*. When searching for numbers, let us assume that climate change becomes catastrophic for ecosystems and life-support systems at a 4 degrees Celsius global average surface temperature increase. Abstract from uncertanties, and assume that we know that such global warming will be reached if cumulative emissions between 2010 and 2100 exceed 5 Teraton CO2 (Edenhofer et al. 2014, Table 6.3). Under unbounded growth, generosity sets this threshold to cumulative emissions.

Unbounded growth leads to the weak condition that only a full catastrophe needs to be prevented. The analysis changes fundamentally, however, if climate change indicators enter utility directly,

$$u_t = u(c_t, m_t), \tag{19}$$

as proposed by Gerlagh and van der Zwaan (2002) and Sterner and Persson (2008).[11] It is important to realize that potential growth without bounds indeed will lead to actual growth without bounds if the return on capital (interest rate) is bounded from above. This enables us to express long-run utility in terms of cumulative emissions:

Remark 2 *Under 'unbounded growth', $A_t \rightarrow \infty$, $f'(0) = \infty$, and a bounded return to capital,* $\sup_t f'(k_t/A) < \infty$*, and climate directly entering utility (19), long-run utility is fully determined by cumulative emissions:*

$$\lim_{t\to\infty} u_t = v(r_\infty) = u(\infty, m_\infty) \tag{20}$$

[11] See Baumgärtner, Drupp and Quaas (2015) for the analysis of a CES function with environmental subsistence consumption.

where

$$m_\infty = m^*(r_\infty) \tag{21}$$

Given non-negative emissions, attainable utility is determined as $\mathcal{A}(k_t, \mathbf{s}_t, m_t) = v(r_t) = u(\infty, m^*(r_t))$. Gerlagh and van der Zwaan (2002) show that for a two-good economy with one ever-growing good and one good that is bounded from above, long-run utility depends on current actions (cumulative emissions, in our case) that determine the long-run level of the bounded good and the specific features of the utility function. They introduce the terms perfect and poor long-term substitutability to characterize different types of utility functions.[12] If man-made consumption goods are a perfect long-term substitute for the environment, $v'(r_t) = u_m(\infty, m^*(r_t)) = 0$, attainable income remains independent of climage change and generosity does not require additional policies. If, however, man-made consumption goods are a poor long-term substitute for the environment, $v'(r_t) > 0$, $u_m(\infty, m^*(r_t)) > 0$, then attainable utility directly changes with current emissions and Proposition 1 and Remark 1 apply: generosity requires maximal abatement, $a = 1$, or security that future generations can negate current emissions.

Besides the two options, perfect and poor long-term substitutability between man-made goods and the environment, it is also possible that there exists a threshold $\overline{m}$ such that man-made goods are a perfect long-term substitute for $m_\infty > \overline{m}$, and a poor long-term substitute for $m_\infty < \overline{m}$ (Gerlagh and van der Zwaan 2002). The third possibilty is the most interesting, as it implies a threshold: emissions are acceptable as long as the long-term consequences do not irreversibly decrease attainable utility.

Proposition 3 *Under non-negative emissions, $a_t \leq 1$, 'unbounded growth', $A_t \to \infty$, $f'(0) = \infty$ and a closed carbon system (8), and climate directly entering utility (19), generosity requires cumulative emissions to be constrained below a threshold*

$$r_t < \overline{r}$$

where

$$m^*(\overline{r}) = \overline{m} \tag{22}$$

Generosity potentially imposes a strong condition, but it will never violate Pareto-efficiency. A corollary of Remark 2, based on Gerlagh and Keyzer (2003, Prop 3), is:

[12] Gerlagh and van der Zwaan (2002) show that in the long run, there is no intermediate case between "perfect" and "poor" long-run substitutability.

Corollary 1 *Under 'unbounded growth', $A_t \to \infty$, $f'(0) = \infty$ and climate directly entering utility (19), a non-generous path never Pareto-dominates a generous path.*

To assess the practical consequences of the above generosity condition, assume that a restriction of cumulative emissions to 1 TtCO2 will keep global warming below 2 degrees Celsius, and assume that at such levels no irreversible damages will occur to eco- and life-support systems, but that any increase above that level will induce irreversible damages. Furthermore, let us assume that these damages are essential, in the sense that they restrict the utility levels that future citizen can reach. Somewhere in between 1 TtCO2 and 5 TtCO2, there is a state of the world where future increased consumption can compensate for the losses associated with climate change, in the sense that it keeps future generations on the same utility level as current generations. Let us say that 4 TtCO2 cumulative emissions allow us to maintain current utility levels at much higher consumption levels but losing much of nature's beauty. The essential outcome of the classic sustainability criterion is that it imposes the 4 TtCO2 threshold as a constraint on society's choices. Generosity, on the other hand, imposes the more stringent 1TtCO2 threshold. Generosity does not admit irreversible and essential damages, but requires that future generations can benefit from unrestricted economic growth and see their utility increase beyond current levels, and not restricted by current actions.

4 Uncertainty and intra-generational inequality

The future is uncertain, and the global distribution of wealth is unequal. Sustainability needs to address both the intergenerational inequity as well as the uncertainty and intra-generational inequality. As in the certainty case above, generosity is more demanding compared to the existing sustainability conditions for a stochastic world (e.g. Asheim and Brekke 2002, Dietz and Asheim 2012), given that we do not focus on the possibility of full catastrophs with fat tails.[13]

Under the axiom of within-period anonymity, the utility allocation at time t is fully captured by the cumulative distribution function for utility levels over all possible states of the world as well as over all individuals within a state of the world. That is, we describe the future in period t through the cumulative distribution function $F_t(u)$, which is the

[13]There is also another literature on uncertainty and risks aversion that approaches the question of sustainable development through the adaption of welfare functions to the stochastic environment (e.g. Traeger 2012, Piacquadio 2014).

share of people with at least utility level u. One can compare the distribution between scenarios or between periods, e.g. period τ dominates another period t, which we write as $F_\tau \succeq F_t$, if the distribution stochastically dominates

$$F_\tau \succeq F_t \text{ iff } \forall u : F_\tau(u) \leq F_t(u)$$

For our exposition here, we follow the convenient approach to aggregate utility within a period, defining a weighted average utility as

$$w_t = \int_0^\infty \alpha(u) u dF_t(u) \tag{23}$$

where we assume that utility levels are defined on the positive domain, and $\alpha(u)$ is the relative weight given to individuals with utility level u. Propositions 2 and 3 naturally extend to this economy with uncertainty and intra-generational inequality. For Proposition 4, however, we need to consider that the environmental changes can affect people's utility differently. Equation (19) becomes

$$u_{t,i} = u_i(c_{t,i}, m_t). \tag{24}$$

where label i represents a consumer at a certain state of the world. The best achievable long run allocation is given by

$$v_i(r_\infty) = u_i(\infty, m_\infty) \tag{25}$$

The corresponding Proposition 4 becomes stronger, in the sense that the maximum cumulative resource use is determined by the consumer type that is most sensitive to climate change damages:

$$\bar{r} = \min_i \{\bar{r}_i\} \tag{26}$$

An action does not satisfy the generosity conditions if there is a state of the world, and a group of consumers with poor long-term substitutability, for whom the maximum attainable utility level is irreversibly reduced. The descendants of the current inhabitants of small islands could be such a group of individuals for the state of the world characterized by sensitive sea-level rise.

5 Discussion

Confronted with the success of worldwide economic growth over the past century, the expected rise of the world middle class in what is still labeled the developing countries, and the threat of the destruction of many of the earth rich ecosystems, including the loss of many small islands due to changing global climate, there is the need for sustainability concepts that provide constructive guidelines which parts of nature we need to conserve, and which parts we can sacrifice in return for higher short-run economic growth (Myers et al. 2000). Part of the literature on sustainability tries to answer these type of questions through axioms that guarantee general applicability to all classes of imaginable economies. However, there is a limit to such a generic approach: it is impossible to construct a welfarist axiology that satisfies a 'complete' set of typical axioms that are considered desirable from an ex-ante perspective (Arrhenius 2000).[14] One interpretation is that for each preference relation one can construct specific cases where there is dispute possible about the resulting ordering. No complete ordering can be constructed that is appealing 'no matter what'. If we cannot construct a welfare ordering that is undisputable in all contexts, it becomes important to understand the realistic context in which we want to test our sustainability criterions, and to specifically ask whether the criterions are appealing in that context.

For the current set of global environmental issues as climate change and biodiversity, a fundamental but also pragmatic question is by how much we should constrain economic expansion to save nature's richness.[15] Classic sustainability paradigms offer clear guidance to avoid disaster if there is evidence that natural losses lead to future generations being strictly worse off compared to present generations. But if one has agreed on avoiding disaster, how much further should one restrict resource use? The analysis presented here offers principles that can be used after one has agreed on preventing catastrophes. Alternatively, we can view the context of this study as typical for most applied assessments (IPCC 2014), which are remarkably optimistic: we can achieve both economic growth and nature's conservation, though conservation may still be costly as it delays income progress. I propose generosity as an extended paradigm for sustainability: to keep or increase instantaneous maximin income (classic sustainability) *and* and to preserve attainable maximin income.

The overall message coming from the concept of generosity is simple. If one beliefs in 'spaceship earth', that is, a finite space where humankind has to make its living for

[14]See Basu and Mitra (2003) for an impossibility theorem to reconcile intergenerational Pareto efficiency and equity.

[15]Thus, the realistic sustainability question is *not* whether the current generation should give up all income and fall into complete poverty to preserve future's attainable utility. If that were the context, generosity might not be the proper criterion.

a long time to come, then we should keep the fundamental opportunities of this limited space intact, as much as possible. Irreversible damages to the system, when reducing the future utility that can be derived from the system, are not generous. If there is a threshold beyond which climate change threatens to destroy ecosystems beyond recovery, then generosity stipulates that we do not cross these thresholds. This specific implication of generosity is much more demanding compared to existing concepts of sustainability, which only require that we compensate future generations by sufficient man-made capital for the loss of environmental capital to make them not worse off compared to us. Generosity requires, rather differently, that environmental resources are protected if their contribution to future utility is bounded away from zero, even if future generations enjoy a higher overall level of utility.

If, on the other hand, one beliefs in infinite ingenuity, where future generations can uncover opportunities that we cannot think of, possibly reaching beyond spaceship earth, then one has to ask which parts of spaceship earth we consider so fundamental to utility that man-made goods coming out of our ingenuity cannot substitute for these, however rich our future descendants may become. The main duty imposed by generosity is then to conserve these fundamental parts, while accepting exhaustion of other parts in return for economic growth.

Though generosity is a strong condition, it does not impose dictatorship of the future (Chichilnisky's 1996). In Chichilnisky's formulation, full dictatorship implies that current generations receive no weight in decision making. In the generosity framework, present decisions are still directed to the maximization of present generation's welfare, and these interests are given full weight in current decisions (see also Gerlagh and Keyzer 2003); only when present actions are in direct conflict with utility of an infinite stream of future generations, and only when the costs to future generations are bounded away from zero, does generosity limit today's actions.

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