A DYNAMIC ANALYSIS OF HUMAN WELFARE IN A WARMING PLANET

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ABSTRACT

"A DYNAMIC ANALYSIS OF HUMAN WELFARE IN A WARMING PLANET"

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Anthropogenic greenhouse gas (GHG) emissions have caused atmospheric concentrations with no precedents in the last half a million years, inducing serious uncertainties about future climates and their effects on human welfare. Recent climate science supports the view that the climate stabilization will require very low GHG emissions in the future. We ask: Is a path of low emissions compatible with sustainable levels of human welfare? With steady growth in human quality of life? Addressing these questions requires both defining welfare criteria and empirically estimating the possible paths of the economy.

We specify and calibrate a dynamic model with four intertemporal links: education, physical capital, knowledge and the environment. In line with Nordhaus (2008a) and with the Stern Review (2007), we assume that GHG emissions allow increased production, while a higher stock of atmospheric carbon decreases production.

Our index of human welfare, which we call *quality of life* (QuoL), emphasizes education, knowledge, and the environment, affected by greenhouse gas emissions, in addition to consumption and leisure. Thus, we avoid a Consumptionist Fallacy – that welfare depends only on commodity consumption and perhaps leisure.

We reject discounted utilitarianism as a normative criterion, and consider two alternatives. The first is an *intergenerational maximin* criterion, which maximizes the quality of life of the first generation subject to maintaining at least that level for all successive generations. The second is *human development optimization*, that seeks the maximization of the QuoL of the first generation subject to achieving a given, constant rate of growth in all subsequent generations. Hence, our analysis focuses on a human notion of sustainability, as opposed to the conventional "green" sustainability, limited to keeping the quality of the environment constant.

Because our dynamic optimization programs defy explicit analytical solutions, our approach has been computational. As a benchmark, we consider a simple model with physical and human capital, for which we prove a turnpike theorem. We then devise a computational algorithm inspired by the turnpike property to construct feasible, although not necessarily optimal, paths in the more complex and realistic model.

Our analysis indicates that, with GHG emission paths entailing very low emissions in the future, positive rates of growth in QuoL are possible while the first generation experiences a QuoL higher than the historical reference level. We also observe a tradeoff between the quality of life of the first generation and the rate of growth in the quality of life. Yet Generation 1's sacrifice for the sake of a higher growth rate appears to be small. The paths that we compute involve investments in knowledge at noticeably higher levels than in the past.

Keywords: Quality of life, climate change, education, maximin, growth.
JEL classification numbers: D63, O40, O41, Q50, Q54, Q56.

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1. Introduction

Human activity at any moment of time influences future possibilities for welfare through the creation and the destruction of various forms of capital. Some of the benefits of an investment accrue within the lifetime of the generation that makes it. Others are intergenerational: the benefits of accumulated knowledge and of preserved natural environments extend far into the future, and therefore have the character of intergenerational public goods. For instance, the knowledge acquired at a given moment can be used with little additional effort at future dates. And many forms of physical capital, such as infrastructure, are useful beyond the lifetimes of the generation that produces them.

But, on the negative side, current production and consumption also deplete nonrenewable resources and deteriorate the environment. The extinction of, say, an animal species affects both the current generation and all subsequent ones, constituting an intergenerational public bad. As noted in Nicholas Stern (2007), to be referred to as the Stern Review, climate change due to anthropogenic greenhouse gas (GHG) emissions is, currently, "the most important externality." We adopt an inclusive approach that simultaneously considers the major intergenerational public goods and bads.

We propose (Section 2.1 below) an encompassing notion of human welfare that includes both consumption and the quality of the environment as arguments. Less conventionally, we also assume that improvements in knowledge and culture, and in education, directly enrich human quality of life.

Next, we view society as comprised of an infinite sequence of generations, and define (Section 2.2 below) two criteria of intergenerational welfare. The first one is John Rawls's (1971) *maximin* criterion, but applied to the various generations. The maximization of this social welfare

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function leads to stationary levels of human welfare, thus capturing the notion of human sustainability.

Because the growth in the quality of life is often considered a worthwhile objective, we also consider a second social welfare function that takes as given a predetermined, constant rate of growth. In any event, we avoid the discounted utilitarian approach, which we find unjustified at least for the discount rates commonly used.

We construct (Section 4) and calibrate a dynamic economic model involving economic and environmental variables. Ideally, we would like to specify a physical climate model, and find the optimal values of all these variables subject to the constraints of the economic and the environmental models. But given the complexity and uncertainties of current climate models, we have adopted a more modest goal. We eschew the specification of a physical model of emission-stock interactions, and consider instead a particular path for the environmental variables, which entails very low emissions after 2050, and realistically appears to be feasible given present knowledge of climate dynamics, as represented by the IPCC AR 4 (2007, Working Group I, *The Physical Science Basis*, Chapter 10), to be referred to in what follows as Gerald Meehl *et al*. (2007).

The economic variables are then endogenous in our optimization programs, while the environmental variables are postulated to follow the prescribed path. We develop a computational algorithm based on the turnpike property (Section 3). We show that positive rates of growth in human welfare are possible while the first generation experiences a quality of life higher than the reference level. The computed paths involve investments in knowledge at noticeably higher levels than in the past.

Last, we comment on the introduction of uncertainty in dynamic welfare analysis (Section 5), and on the relation of our result with the literature, particularly on the Stern Review and the work of William Nordhaus and his collaborators (Section 6), and summarize our results (Section 7).

2. Our approach

2.1. The Quality-of-Life function

A large segment of the literature (e. g., Nordhaus, 2008a) postulates an individual or generational utility function with the consumption of a single, produced good as its only argument (sometimes augmented by leisure time). It therefore suffers from a *consumptionist fallacy*:

improvements in knowledge, education, and the environment are important only in so far as they make possible the production of consumption goods with less labor time or capital.

In fact, both the consumption of goods and the availability of natural capital positively affect human welfare. Indeed, the spectacular increase of consumption in developed economies during the last century has undoubtedly provided a major welfare improvement (D. G. Johnson, 2000). But, in our view, two other factors have also had major impacts. First are the improvements in life expectancy, health status and infant survival, partly due to the rise in consumption, but to a large extent due to medical discoveries, and their implementation by the public health system.[2] Second is the improvement in literacy and, more generally, in the amount of education received by the average person, which has enhanced not only the productivity of labor but also the quality of life: the contribution of leisure to the quality of life increases as leisure time embodies higher levels of human capital, see Salvador Ortigueira (1999) and Martin Wolf (2007), as well as J. J. Heckman (1976) and R. T. Michael (1973). In Martin Wolf's words:

> "The ends people desire are, instead, what makes the means they employ valuable. Ends should always come above the means people use. The question in education is whether it, too, can be an end in itself and not merely a means to some other end – a better job, a more attractive mate or even, that holiest of contemporary grails, a more productive economy. The answer has to be yes. The search for understanding is as much a defining characteristic of humanity as is the search for beauty. It is, indeed, far more of a defining characteristic than the search for food or for a mate. Anybody who denies its intrinsic value also denies what makes us most fully human."

Accordingly, we focus on human *quality of life* (QuoL) (not "utility," "welfare," or the now fashionable "happiness," as in the recent research by Daniel Kahneman, Daniel McFadden, Alan Krueger, Richard Layard and others).[3] The quality of life will be denoted by the Greek letter Λ instead of the customary U or W, which would suggest "utility" or "welfare." Our approach follows the spirit of the Human Development Index (HDI) produced by the United Nations Development Program, which considers three dimensions, namely (a) life expectancy, (b) education, and (c) consumption (GDP per capita).

[2] Jim Oeppen and James Vaupel (2002, p. 1029) report that "female life expectancy in the record-holding country has risen for 160 years at a steady pace of almost 3 months per year."

[3] See, e. g., Krueger and Kahneman (2006), Layard (2005), McFadden (2005) and the contributions in Kahneman, Diener and Schwartz, editors (1999).

The first argument in the quality-of-life function is consumption. But we aim at avoiding the *consumptionist fallacy* by emphasizing other factors as well:

(i) Education, which modifies the value of leisure time to the individual;

(ii) Knowledge, in the form of society's stock of culture and science, which directly increases the value of life (in addition to any indirect effects through productivity), via improvements in health and life expectancy, and because an understanding of how the world works and an appreciation of culture are intrinsic to human well-being.

(iii) An undegraded biosphere, which is valuable to humans for its direct impact on physical and mental health.[4]

Hence, we put consumption, educated leisure, the stock of human knowledge, and the quality of the biosphere into the quality-of-life function. The first two arguments are private goods, and the last two are public goods.

Note the possible consequences of this move. In traditional growth theory, improvements of human welfare are engendered either by increases in commodity consumption or leisure. If we wish to contemplate the possibility of slowing down the rate of commodity consumption, the only possibility for continuing to increase welfare is that people spend more time in leisure. While one may interpret 'leisure activities' in multifarious ways, these are not made explicit in the models, but are left to the imagination of the reader. To the contrary, our approach is explicit with respect to ways in which mankind can enjoy improved welfare, aside from increasing its material consumption or leisure time: the *value* of leisure may be increased through more intensive education, the quality of the biosphere may be improved, and the stock of social knowledge may be increased. 'Leisure activities' need not do all the work.

We abstract from all conflicts except for the intergenerational one and, accordingly, we assume a representative agent in each generation. Formally, we postulate the following quality-of-life (QuoL) function of Generation t, $t \geq 1$:

$$\tilde{\Lambda}(c_t, x_t^l, S_t^n, S_t^m) \equiv (c_t)^{\alpha_c} (x_t^l)^{\alpha_l} (S_t^n)^{\alpha_n} (\hat{S}^m - S_t^m)^{\alpha_m}, \qquad (1)$$

where the exponents are positive and normalized such that

[4] This is captured in the Cost-Benefit literature on global warming by the computation of the so-called "noneconomic effects."

$$\alpha_c + \alpha_l + \alpha_m + \alpha_n = 1.$$

We assume that a generation lives for 25 years, and define the variables as follows:

c_t = annual average consumption per capita (in thousands of dollars) by Generation t ;

x_t^l = annual average leisure per capita, in efficiency units, by Generation t;

S_t^n = stock of knowledge per capita, which enters Generation t's quality-of-life function and production function, measured in thousands of dollars (per capita), understood as located in the last year of life of Generation t,

S_t^m = total CO_2 in the atmosphere above the equilibrium pre-industrial level, in GtC, which is understood as located in the last year of life of Generation t;[5] and

$\hat{S}^m$ = "catastrophic" level of CO_2 in the atmosphere above the equilibrium pre-industrial level.

The presence of the stock of CO_2 in the QuoL function captures our view that environmental deterioration is a public bad in consumption, contrary to the modeling of Nordhaus (1994, 2008a) and Nordhaus and Boyer (2000), where it is only a public bad in production.

Appendix 5 explains our calibration procedure for the parameters α_c, α_l , α_m , α_n and $\hat{S}^m$.

2.2. Optimization programs: Sustainable quality of life vs. human development

We are concerned with *human sustainability*, which requires maintaining human quality of life, rather than *green sustainability*, which can be defined as keeping the quality of the biosphere constant.[6] This objective can be justified by appealing to the Maximin principle, see Roemer (1998, 2007). It can be argued, and this is Rawls's position when justifying the (contemporaneous) "difference principle," that it is the quality of life of each person that should enter the maximin calculus, rather than subjective utility, which generally includes the satisfaction that the individual derives from the welfare of other people, such as her children.

Maximizing the quality of life of the worst-off generation will often require the maximization of the quality of life of the first generation subject to maintaining that quality of life

[5] The preindustrial values for the CO_2 stock are taken to be 595.5 GtC or 280 ppm. To convert our S_t^m into CO_2 ppm, add 595.5 to S_t^m and multiply by 0.47. To convert a number of CO_2 ppm into our S_t^m , subtract 280 from it and multiply by 2.13.

[6] See the discussion of Strong and Weak Sustainability in Section 6.1.

for all future generations, so that there is no *human development* after the first generation.[7] Formally, the optimization program is of the following type.

<u>Maximin Program</u>

max Λ subject to:

$$(c_t)^{\alpha_c}(x_t^l)^{\alpha_l}(S_t^n)^{\alpha_n}(\hat{S}^m - S_t^m)^{\alpha_m} \geq \Lambda,\ t \geq 1,$$

and subject to the feasibility conditions given by specific production relations, laws of motion of the stocks and resource constraints, and with the initial conditions given by the relevant stock values in the base year (2000).

At a solution of the Maximin Program, the path of the quality of life will typically be stationary, and it can be (at least asymptotically) supported by stationary paths in all the arguments of the QuoL function.

The Maximin Program models sustainability in our sense. Alternatively, the planner may seek a positive rate of growth in the QuoL of future generations at the cost of reducing the quality of life of Generation 1. It is, however, not obvious how to justify sacrifices of the worst-off present generation for the sake of improving the already higher quality of life of future ones.[8]

One might argue that parents want their children to have a higher quality of life than they do. Thus, growth of the quality of life might be supported by all parents over the maximin solution. However, this would presumably not be supported by childless adults, who were otherwise not altruistic.

A more universal justification for altruism towards future generations would appeal to *human development as a public good*: we may feel justifiably proud of mankind's recent gains in, say, extraterrestrial travel, or average life expectancy, and wish them to continue into the far future even at a personal cost.[9]

Indeed, there is an asymmetry in the way we feel about contemporaneous vs. temporally disjoint inequality: a person in a poor country may not wish to sacrifice her quality of life for the sake of improving that of a person in a *richer* country, while at the same time be willing to make

[7] But not always: see Silvestre (2002).
[8] Recall that we assume away intragenerational inequality, thereby depriving economic growth of a role in alleviating contemporaneous poverty. This important topic has high priority in our research agenda.
[9] See Silvestre (2007).

some sacrifices for the welfare of unrelated, yet-to-be born individuals who will as a consequence be richer than she.

Assume that society wants to achieve a sustained rate ρ of growth in the future quality of life: instead of maximizing the quality of life of the worst-off generation, it aims at the maximization of the quality of life of the first generation, subject to the condition that the quality of life subsequently grows at a given rate ρ per generation. The optimization program then becomes:

Human Development Optimization Program

max Λ subject to:

$$(c_t)^{\alpha_c}(x_t^l)^{\alpha_l}(S_t^n)^{\alpha_n}(\hat{S}^m - S_t^m)^{\alpha_m} \geq (1+\rho)^{t-1}\Lambda,\ t \geq 1,$$

for $\rho \geq 0$ given, and subject again to the feasibility and initial conditions.

Note that the Maximin Program can be written in this form by letting $\rho = 0$.

At a solution to this program, the quality of life grows at a constant rate, but it is impossible to have steady positive growth of all variables because of the finite capacity $\hat{S}^m$ of the biosphere.

We study the Maximin and Human Development Optimization programs under various specifications of the feasibility constraints, in particular under various assumptions on the relationship between the production of output and the emissions of GHG. We develop computing algorithms based on the turnpike property that some growth models display. We first discuss a simple growth model, without environmental or knowledge stocks, but with investment in physical and human capital, which does display the turnpike property.

3. The turnpike property in a benchmark sustainability model with human and physical capital

This is a simple model with only education and physical capital as intertemporal links. Recall that t = 1, 2, …. is measured in generations (25 years).

Benchmark Model

Quality of life function: $c_t^{\alpha}(x_t^l)^{1-\alpha}$;

Aggregate production function: $\hat{k}_2(S_t^k)^{\theta}(x_t^c)^{1-\theta}$;

Law of motion of physical capital: $(1-\tilde{\delta})S_{t-1}^k + i_t \geq S_t^k, \quad t \geq 1,$

Allocation of efficiency units of time: $x_t^e + x_t^l + x_t^c \equiv x_t, \quad t \geq 1,$

Education production function: $\hat{k}_4 x_{t-1}^e \geq x_t, \quad t \geq 1,$

with (x_0^e, S_0^k) as initial condition (or "endowment") vector, where c_t and x_t^l have been defined in the specification of the quality of life function in Section 2.1 above, and where:

x_t^c = average annual efficiency units of labor per capita devoted to the production of output by Generation *t*;

S_t^k = capital stock per capita (in thousands of dollars) available to Generation *t*;

i_t = average annual investment per capita (in thousands of dollars) by Generation *t*;

x_t^e = average annual efficiency units of labor per capita devoted to education by Generation *t*;

x_t = average annual efficiency units of time (labor and leisure) per capita available to Generation *t* .

We are to find the maximum level Λ of sustainable quality of life for this fairly straightforward infinitely lived economy. To that end, we consider the following maximin program.

Program SUS. Max Λ subject to:

$$c_t^{\alpha} (x_t^l)^{1-\alpha} \geq \Lambda, \quad t \geq 1,$$

$$\hat{k}_2 (S_t^k)^{\theta} (x_t^c)^{1-\theta} \geq c_t + i_t, \quad t \geq 1,$$

$$(1-\tilde{\delta}) S_{t-1}^k + i_t \geq S_t^k, \quad t \geq 1,$$

$$x_t^e + x_t^l + x_t^c \equiv x_t, \quad t \geq 1,$$

$$\hat{k}_4 x_{t-1}^e \geq x_t, \quad t \geq 1,$$

and the initial conditions (x_0^e, S_0^k) .

Even though the model is not realistic enough for our purposes to warrant calibration, it is interesting as a reference because its optimal path has the turnpike property, in the sense popularized by classical optimal growth theory. First we find a (unique) ray $\hat{\Gamma}$ of initial endowments in $\Re_+^2$ for which the solution path is *stationary*, that is, for which all variables are constant over time. The main result then takes the following form.

Theorem 1 (Turnpike Theorem)

1. *There is a ray* $\hat{\Gamma} \in \Re^2_+$ *such that, if* $(x^e_0, S^k_0) \in \hat{\Gamma}$ *, then the solution path to Program SUS is stationary.*

2. *If* $(x^e_0, S^k_0) \notin \hat{\Gamma}$ *, then along the solution path to Program SUS the sequence* (x^e_t, S^k_t) *converges to a point on* $\hat{\Gamma}$.

3. *Along the solution path, all constraints hold with equality* (*in particular, the quality of life is constant over t*).

Proof. Appendix 1.

Figure 1 illustrates parts 2 and 3 of Theorem 1. The solution path determined by initial conditions off ray $\hat{\Gamma}$ has constant quality of life, and it has the property that, along this path, the sequence converges to a point in $\hat{\Gamma}$.

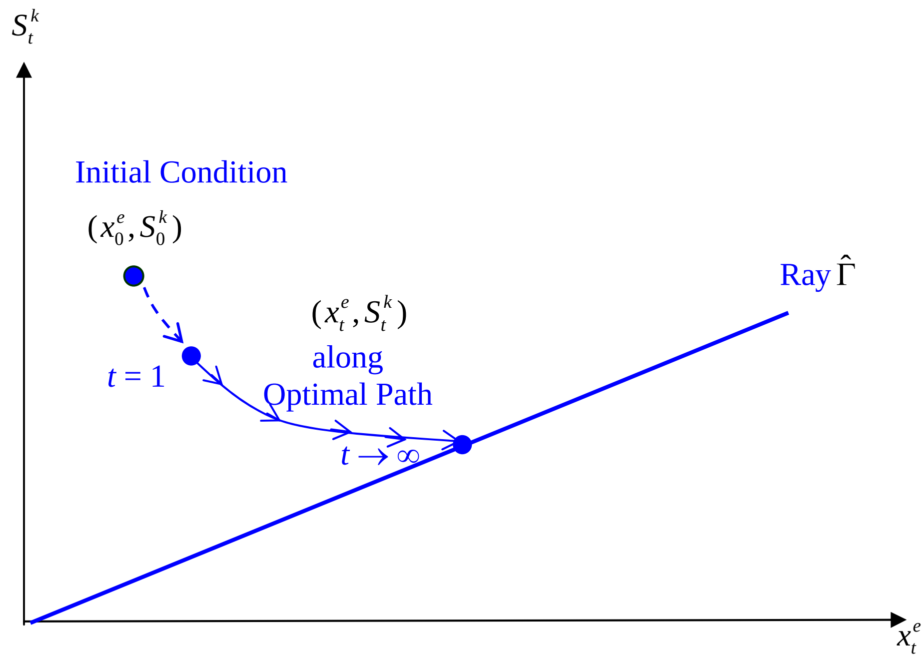

Figure 1
Convergence to ray $\hat{\Gamma}$

4. The full model with economic and environmental constraints

4.1. Feasibility

Feasible paths are characterized by the following constraints. Inequalities (2)-(4), (6) and (7) are the *economic constraints*, and their parameters are calibrated in Appendix 4 below. Condition (5) is the environmental constraint.

$$f(x_t^c, S_t^k, S_t^n, e_t, S_t^m) \equiv k_{11}(x_t^c)^{\theta_c}(S_t^k)^{\theta_k}(S_t^n)^{\theta_n}(e_t)^{\theta_e}(S_t^m)^{\theta_m} \geq c_t + i_t,\ t \geq 1, \quad (2)$$

with $\theta_c > 0$, $\theta_k > 0$, $\theta_n > 0$, $\theta_c + \theta_k + \theta_n = 1$, $\theta_e > 0$, $\theta_m < 0$,

(Aggregate production function *f*)

$$(1-\delta^k)S_{t-1}^k + k_5 i_t \geq S_t^k,\ t \geq 1, \text{ (Law of motion of physical capital)} \quad (3)$$

$$(1-\delta^n)S_{t-1}^n + k_2 x_t^n \geq S_t^n,\ t \geq 1, \text{ (Law of motion of the stock of knowledge)} \quad (4)$$

$$\{(e_t, S_t^m)_{t=1}^{\infty}\} \in \Pi, \text{ (Flow-stock physical feasibility for emissions)} \quad (5)$$

$x_t^e + x_t^c + x_t^n + x_t^l \equiv x_t$, $t \geq 1$, (Allocation of efficient units of labor) (6)

$k_4 x_{t-1}^e \geq x_t$, (Education production function) (7)

with initial conditions (x_0^e, S_0^k, S_0^n), where c_t, x_t^l, S_t^n, S_t^m and $\hat{S}^m$ have been defined in the specification of the quality of life function in Section 2.1 above, S_t^k, i_t, x_t^e, x_t^c and x_t have been defined in the Benchmark Model of Section 3 above, and where:

x_t^n = average annual efficiency units of labor per capita devoted to the production of knowledge by Generation *t*,

e_t = average annual emissions of CO_2 in GtC by Generation *t*.

Π is an abstract set of infinite paths of emission-concentration pairs (e_t, S_t^m), starting at $t = 1$, that comply with known physical laws and historical values preceding $t = 1$.

We call emissions e_t and concentrations S_t^m *environmental variables*, whereas the remaining variables are called *economic*. Note that the environmental variables are arguments in the production function *f*, an approach which is often adopted, explicitly or implicitly, in the literature.

4.2. The environmental constraint

Anthropogenic greenhouse gas (GHG) emissions have caused atmospheric concentrations with no precedents in the last half a million years: see Figure 2, reproduced from Pierre Friedlingstein and Susan Salomon (2005). The unparalleled behavior of GHG concentrations has motivated a growing literature that tries to predict the relationship among the paths of emissions, concentrations and global temperature changes. Because of the complexity of the climate models proposed and the lack of a canonical physical model in the current state of climatology, we adopt the abstract formulation (5) of the paths for the environmental values in lieu of postulating a specific law of motion.

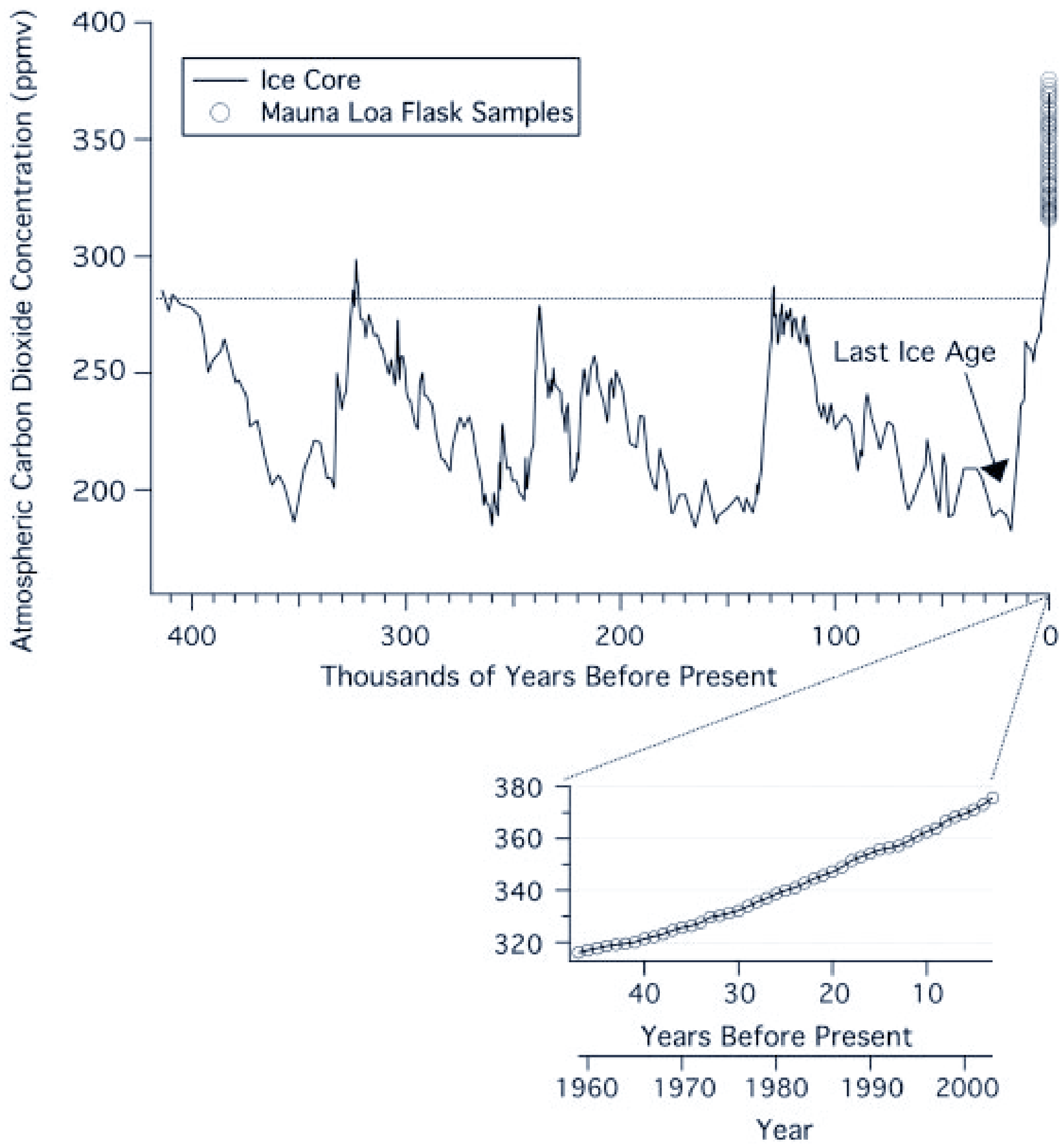

Figure 2
Observed CO_2 concentrations vs. time based on ice-core records spanning over 400,000 years, and flask-air examples spanning almost 50 years. Note the different time scales in the Figure and Inset. (Reproduction of Figure 1 in Friedlingstein and Solomon, 2005.)

We follow a large segment of literature and focus on CO_2 emissions and concentrations.[10] Recent climate research has revised upwards the persistence of the effects of GHG emissions. Haaron Kheshgi, Steven Smith and James Edmonds (2005, p. 213) emphasize that emitted CO_2 "is not destroyed in the atmosphere, but redistributed amongst the reservoirs that actively exchange carbon: plants and soils, oceans and the atmosphere." They argue that "for CO_2 to approach a constant concentration over finite time, CO_2 emissions must peak and then gradually approach zero over 1,000+ years, regardless of the concentration level." Alvaro Montenegro *et al*. (2007, p.1) argue that "higher levels of atmospheric CO_2 remain in the atmosphere than predicted by previous experiments, and the average perturbation lifetime of emissions is much longer than the 300-400 years proposed by other studies." Based on new evidence on the behavior of ocean temperatures after increases in emissions, H. Damon Matthews and Ken Caldeira (2008) show that temperatures will be rising long after the CO_2 concentration in the atmosphere has been stabilized and that in order "to achieve atmospheric carbon dioxide levels that lead to climate stabilization, the net addition of CO_2 to the atmosphere from human activities must be decreased to nearly zero." Similar conclusions are reached by Friedlingstein and Solomon (2005).

We do not attempt to specify the set Π and, accordingly, we do not try to compute optimal paths for emissions and the environmental stock. Instead, we adopt simple paths inspired by Meehl *et al*. (2007, Section 10.4), in particular by emission paths that lead to relatively low levels of stabilized concentrations of CO_2 under the assumption of coupling between climate change and the carbon cycle: The growth of the atmospheric CO_2 induces a climate change that affects the carbon cycle.[11] Section 4.4 below describes the numerical values adopted in our computations.

In any event, it is impossible to have steady (positive) growth of all variables because of the finite capacity $\hat{S}^m$. Because we nevertheless wish to examine paths for all the other economic variables where the quality of life grows at a constant rate (perhaps zero), we elect to study paths of emissions and the stock of CO_2 that converge in three generations to a stabilized concentration S^{m*} of atmospheric CO_2.

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[10] The long-term effects of non-CO_2 GHG emissions have been addressed in particular by Marcus Sarofim *et al*. (2005).

[11] In their words (p. 789) "There is an unanimous agreement among the models that future climate change will reduce the efficiency of the land and ocean carbon cycle to absorb anthropogenic CO_2, essentially owing to a reduction in the land carbon uptake."

Most of the more recent and detailed physical models have no steady states, in the strict sense, with positive emissions. But if emissions are steady at low enough levels, then the stock of GHG eventually grows very slowly, experiencing minor increases in a scale of thousands of years. The stocks of GHG are then said to be "stabilized" even though, strictly speaking, they are not constant in the very long run. Here we assume a constant "long term" value of the stock of GHG, where "constant" is a simplification of "stabilized," and where the "long term" scale refers to a few hundreds, but not thousands, of years.

4.3. The ray optimization theorem

The following result underpins our computational strategy. Consider a pair (e^*, S^{m*}) such that $\{(e^*, S^{m*})_{t=1}^{\infty}\} \in \Pi$, and the following optimization program.

Program $E[\rho, e^*, S^{m*}]$

Given (ρ, e^*, S^{m*}), Max Λ_1 subject to

$$
\begin{aligned}
& c_t^{\alpha_c}(x_t^l)^{\alpha_l}(S_t^n)^{\alpha_n}(\hat{S}^m - S^{m*})^{\alpha_m} \geq \Lambda_1(1+\rho)^{t-1}, t \geq 1, \\
& k_{11}(x_t^c)^{\theta_c}(S_t^k)^{\theta_k}(S_t^n)^{\theta_n}(e^*)^{\theta_e}(S^{m*})^{\theta_m} \geq c_t + i_t, \quad t \geq 1, \\
& (1-\delta^k)S_{t-1}^k + k_5 i_t \geq S_t^k, \quad t \geq 1, \\
& (1-\delta^n)S_{t-1}^n + k_2 x_t^n \geq S_t^n, \quad t \geq 1, \\
& x_t^e + x_t^n + x_t^l + x_t^c \equiv x_t, \quad t \geq 1, \\
& k_4 x_{t-1}^e \geq x_t, \quad t \geq 1,
\end{aligned}
$$

with initial conditions (x_0^e, S_0^k, S_0^n).

Recall that ρ is the rate of growth of the QuoL per generation. It will be convenient to denote by g the rate of growth of the economic variables, again per generation.

Theorem 2. *Assume constant returns to scale in production in the sense that* $\theta_c + \theta_k + \theta_n = 1$. *Given* $(g, e^*, S^{m}*) \in \Re_+ \times \Re_{++} \times \Re_{++}$, *there is a ray*

$$\Gamma(g, e^*, S^{m}*) \equiv \{(x^e, S^k, S^n) \in \Re_+^3 : (S^k, S^n) = x^e(q^k(g, e^*, S^{m*}), q^n(g))\},$$

such that if $(x_0^e, S_0^k, S_0^n) \in \Gamma(g, e^*, S^{m*})$, $(x_0^e, S_0^k, S_0^n) \neq 0$, *then the solution path to Program* $E[\rho, e^*, S^{m*}]$ *satisfies:*

(i) $(x_t^e, S_t^k, S_t^n) = (1+g)^t (x_0^e, S_0^k, S_0^n)$, $t \geq 1$, *and hence* $(x_t^e, S_t^k, S_t^n) \in \Gamma(g, e^*, S^{m*})$, $t \geq 0$;

(ii)

$$c_1 = p^c(g)q^k(g,e^*,S^{m*})\,x_0^e,$$
$$i_1 = p^i(g)q^k(g,e^*,S^{m*})\,x_0^e,$$
$$x_1^l = \nu^l(g)q^n(g)\,x_0^e,$$
$$x_1^n = \nu^n(g)q^n(g)\,x_0^e,$$
$$x_1^c = \nu^c(g)q^n(g)\,x_0^e;$$

(iii) $(c_t, i_t, x_t^l, x_t^n, x_t^c) = (1+g)^{t-1}\ (c_1, i_1, x_1^l, x_1^n, x_1^c)$, $t \geq 1$.

The quality of life grows at rate ρ, *were* $1+\rho = (1+g)^{1-\alpha_m}$ *, and all other variables grow at rate* $1+g$ *,* except for emissions and concentrations, which remain constant at (e^*, S^{m*}).

Proof. Appendix 2, where the various proportionality factors (q, p, ν) are computed in terms of the parameters of the model. Table 1 illustrates the theorem.

	STOCKS				FLOWS				QuoL
Initial Conditi	x_0^e	$S_0^k = q^k x_0^e$	$S_0^n = q^n x_0^e$						
t=1	$x_1^e = (1+g)x_0^e$	$S_1^k = q^k x_1^e = (1+g)S_0^k$	$S_1^n = q^n x_1^e = (1+g)S_0^n$	S^{m*}	e^*	$c_1 = p^c q^k x_0^e$	$i_1 = p^i q^k x_0^e$	$x_1^j = \nu^j q^k x_0^e$, $j = l,n,c$	Λ_1
t =2	$x_2^e = (1+g)^2 x_0^e$	$S_2^k = q^k x_2^e = (1+g)^2 S_0^k$	$S_2^n = q^n x_2^e = (1+g)^2 S_0^n$	S^{m*}	e^*	$c_2 = p^c q^k x_1^e = (1+g)c_1$	$i_2 = p^i q^k x_1^e = (1+g)i_1$	$x_2^j = \nu^j q^k x_1^e = (1+g)x_1^j$, $j = l,n,c$	$(1+\rho)\Lambda_1$
t	$x_t^e = (1+g)^t x_0^e$	$S_t^k = q^k x_t^e = (1+g)^t S_0^k$	$S_t^n = q^n x_t^e = (1+g)^t S_0^n$	S^{m*}	e^*	$c_t = p^c q^k x_{t-1}^e = (1+g)^{t-1} c_1$	$i_t = p^i q^k x_{t-1}^e = (1+g)^{t-1} i_1$	$x_t^j = \nu^j q^k x_{t-1}^e = (1+g)^{t-1} x_1^j$, $j = l,n,c$	$(1+\rho)^{t-1}\Lambda_1$

Table 1. Stocks and flows in Theorem 2.

In particular, it is important to observe that, for $g = \rho = 0$, whenever the initial endowments (x_0^e, S_0^k, S_0^n) lie in $\Gamma(0, e^*, S^{m^*})$, the solution to Program $E[0, e^*, S^{m^*}]$ is stationary over time.

Furthermore, we conjecture that a turnpike theorem, analogous to Theorem 1, is true for this model for any *g*, and so, if we begin with an endowment vector off the ray $\Gamma(g, e^*, S^{m^*})$, then the optimal solution to Program $E[\rho, e^*, S^{m^*}]$ will converge to the ray $\Gamma(g, e^*, S^{m^*})$. Hence, in the long run, the solution will be almost a steady-state path.

4.4. Environmental paths

Motivated by our conjecture that the optimal solution to Program *E* asymptotically approaches steady-state growth, and therefore that the stocks approach the ray $\Gamma(g, e^*, S^{m^*})$, in this section we construct feasible paths which begin at the actual year-2000 endowment values $(\bar{x}_0^e, \bar{S}_0^k, \bar{S}_0^n)$ and reach the ray $\Gamma(g, e^*, S^{m^*})$ in two generations, where (e^*, S^{m^*}), as well as the magnitudes for the first two generations, are based on the conclusions of Meehl *et al*. (2007).[12]

More precisely, for various rates of growth $\rho \geq 0$ of the quality of life (or associated rates of growth *g* of the variables), we construct feasible paths ($\Lambda_1, \Lambda_2, \ldots$) such that the ratio $\frac{\Lambda_t}{\Lambda_{t-1}}$ of quality-of-life growth experienced by the later generations $t \geq 2$ is $1+\rho$, and analyze the implications of these sustained growth factors for the quality of life Λ_1 of Generation 1. A reference level of QuoL is the one determined by the year-2000 values of the relevant variables, to be denoted Λ_0.

As explained in Section 4.3 above, our starting point are the estimates provided by Meehl *et al*. (2007, Section 10.4). We choose the target stabilization level of 450 ppm (Meehl *et al.*, 2007, Section 10.4, Figure 10.21(a)) and, conservatively, the path of coupled emissions for the Hadley model, as in C. D. Jones *et al*. (2006) (Figure 10.21.(c)).

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[12] Inspired by IPCC AR4 (2007), we have computed paths in which carbon concentrations converge to the stabilized level in two generations. However, our optimization program could be run for slower convergence paths, with convergence in three or more generations, at the cost of additional complexity in computation. We have also tried to maximize the QuoL of Generation 1 subject to its reaching the ray. Note that Generation 1's investment in knowledge (which affects the QuoL of Generation 1 both directly and indirectly through production) and Generation 1's investment in physical capital (which affects the QuoL of Generation 1 only indirectly through production) create intergenerational public goods. It turns out that, even for a zero-growth target, when Generation 1 maximizes its own QuoL subject to the stock proportionality dictated by the ray, it invests so heavily as to make the QuoL of the future generations higher that its own, a feature formally similar to the one discussed in Silvestre (2002). The resulting path yields therefore an unnecessarily low value. It is for this reason that we choose Generation 2 as the first one that has stocks on the ray.

These paths involve increasing emissions in the near future, and drastically reduced emissions in the more distant future. We adopt this general pattern, but we simplify the path by postulating only three levels of emissions and stock, which average over each generation the abovementioned lifetime paths for emissions, while taking as stock values those dated at the end of the life of the generation. Hence, the Meehl *et al*. (2007) analysis justifies the feasibility of our paths.

We denote these three (emission, concentration) pairs as:

$(e_1, S_1^m) = (6.97, 303)$ for Generation 1,

$(e_2, S_2^m) = (4.43, 354)$ for Generation 2,

and $(e*, S^m*) = (0.4, 363)$ for Generation *t*, $t \geq 3$.

Our choices for (e_1, S_1^m), (e_2, S_2^m) and $(e*, S^m*)$ imply that, in 2075, the concentration of CO_2 in the atmosphere is of 450 ppm (this corresponds to our value of $S^m* = 363$ GtC in the atmospheric stock of CO_2 beyond the preindustrial stock, see footnote 7 above), which is also the "low target" in the Stern Review.

4.5. Computational algorithm

Ideally, we would like to solve the maximization problems subject to the initial conditions and the postulated emission-stock path. Instead, we construct an algorithm, inspired by turnpike theory, in two steps. First, we solve the optimization problem for (endogenous) initial conditions guaranteeing that the optimal solution is a steady state (i.e., all economic variables, not including the environmental ones, grow at the same, predetermined rate.) Second, we construct an algorithm that goes from the historical initial conditions to the steady state path in two generations, while keeping the rate of growth of the QuoL for all generations after the first one at the predetermined rate.

The quality of life of Generation *t* is given by $c_t^{\alpha_c} (x_t^l)^{\alpha_l} (S_t^n)^{\alpha_n} (\bar{S} - S_t^m)^{\alpha_m}$. If all variables (except the biosphere) grow at a rate *g*, then the quality of life will grow at rate ρ where $1 + \rho = (1 + g)^{1-\alpha_m}$.

A balanced growth solution relative to our choice requires three growth rates:

g for the variables $(S^n, x^n, x^e, x^c, x^l)$,

γ for the variables *i*, *c* and S^k,

ρ for the quality of life.

But ρ and γ are functions of g: so there is one independently chosen growth rate. If $\theta_c + \theta_k + \theta_n = 1$, then we have $g = \gamma$.

We apply the following two-step algorithm for the chosen $(\rho, e_1, S_1^m, e_2, S_2^m, e^*, S^{m*})$.

Step 1. For an arbitrary x_2^e, solve the following program.

Program $G[x_2^e]$. Given $(\rho, e_1, S_1^m, e_2, S_2^m, e^*, S^{m*})$ and x_2^e, Max Λ_1 subject to

$$c_1^{\alpha_c}(x_1^l)^{\alpha_l}(S_1^n)^{\alpha_n}(\hat{S}^m - S_1^m)^{\alpha_m} \geq \Lambda_1,$$

$$c_2^{\alpha_c}(x_2^l)^{\alpha_l}(S_2^n)^{\alpha_n}(\hat{S}^m - S_2^m)^{\alpha_m} \geq (1+\rho)\Lambda_1,$$

$$(x_2^e, S_2^k, S_2^n) \in \Gamma(g, e^*, S^{m*}),$$

$$k_{11}(x_1^c)^{\theta_c}(S_1^k)^{\theta_k}(S_1^n)^{\theta_n}(e_1)^{\theta_e}(S_1^m)^{\theta_m} \geq c_1 + i_1,$$
$$k_{11}(x_2^c)^{\theta_c}(S_2^k)^{\theta_k}(S_2^n)^{\theta_n}(e_2)^{\theta_e}(S_2^m)^{\theta_m} \geq c_2 + i_2,$$
$$(1-\delta^k)S_0^k + k_5 i_1 \geq S_1^k,$$
$$(1-\delta^k)S_1^k + k_5 i_2 \geq S_2^k,$$
$$(1-\delta^n)S_0^n + k_2 x_1^n \geq S_1^n,$$
$$(1-\delta^n)S_1^n + k_2 x_2^n \geq S_2^n,$$
$$k_4 x_0^e \geq x_1^e + x_1^n + x_1^l + x_1^c$$
$$k_4 x_1^e \geq x_2^e + x_2^n + x_2^l + x_2^c,$$

for the initial conditions $(x_0^e, S_0^k, S_0^n) = (\bar{x}_{2000}^e, \bar{S}_{2000}^k, \bar{S}_{2000}^n)$: here and in what follows, the year-2000 value for a variable is indicated by an overbar and a 2000 subscript. See A4.9 below for year-2000 numerical values.

Table 2 illustrates Step 1 in our computation procedure.

	STOCKS				FLOWS				QuoL
Year 2000	$\bar{x}^e_{2000}$	$\bar{S}^k_{2000}$	$\bar{S}^n_{2000}$	$\bar{S}^m_{2000}$	$\bar{e}_{2000}$	$\bar{c}_{2000}$	$\bar{i}_{2000}$	$\bar{x}^j_{2000}$, $j = l,n,c$	$\bar{\Lambda}_{2000}$
t=1	x^e_1	S^k_1	S^n_1	S^m_1	e_1	c_1	i_1	x^j_1, $j = l,n,c$	Λ_1
t=2	x^e_2	$S^k_2 = q^k x^e_2$	$S^n_2 = q^n x^e_2$	S^m_2	e_2	c_2	i_2	x^j_2, $j = l,n,c$	$(1+\rho)\Lambda_1$
t=3	$x^e_3 = (1+g)x^e_2$	$S^k_3 = q^k x^e_3 = (1+g)S^k_2$	$S^n_3 = q^n x^e_3 = (1+g)S^n_2$	S^{m*}	e^*	$c_3 = p^c q^k x^e_2$	$i_3 = p^i q^k x^e_2$	$x^j_3 = \nu^j q^k x^e_2$, $j = l,n,c$	Λ_3
t=4	$x^e_4 = (1+g)^2 x^e_2$	$S^k_4 = q^k x^e_4 = (1+g)^2 S^k_2$	$S^n_4 = q^n x^e_4 = (1+g)^2 S^n_2$	S^{m*}	e^*	$c_4 = p^c q^k x^e_3 = (1+g)c_3$	$i_4 = p^i q^k x^e_3 = (1+g)i_3$	$x^j_4 = \nu^j q^k x^e_3 = (1+g)x^j_3$, $j = l,n,c$	$(1+\rho)\Lambda_3$
$t\geq 4$	$x^e_t = (1+g)^{t-2} x^e_2$	$S^k_t = q^k x^e_t = (1+g)^{t-2} S^k_2$	$S^n_t = q^n x^e_t = (1+g)^{t-2} S^n_2$	S^{m*}	e^*	$c_t = p^c q^k x^e_{t-1} = (1+g)^{t-3} c_3$	$i_t = p^i q^k x^e_{t-1} = (1+g)^{t-3} i_3$	$x^j_t = \nu^j q^k x^e_{t-1} = (1+g)^{t-3} x^j_3$, $j = l,n,c$	$(1+\rho)^{t-3}\Lambda_3$

Table 2. Step 1 in our computation procedure, where
$q^k = q^k(g, e^*, S^{m*}), q^n = q^n(g), \nu^j = \nu^j(g)(j = l,n,c), p^j = p^j(g)(j = c,i)$.

Step 2. Note that the QuoL of Generation 3, and of all subsequent generations, is determined by x^e_2. By trial and error, we locate the value of x^e_2 with the property that, at the solution to Program $G[x^e_2]$, the QuoL of Generation 3 equals $(1 + \rho)^2\Lambda_1$. Note that then the QuoL of Generation t, $t \geq 4$, is $(1 + \rho)^{t-3}$ times the QuoL of Generation 3 (by Theorem 2), and that, by the second constraint of

Program $G[x_2^e]$, the QuoL of Generation 2 is $(1 + \rho)\Lambda_1$. Hence, the QuoL of Generation t is $(1+\rho)^{t-1}\Lambda_1$, for all $t \geq 1$.

Appendix 3 writes the solution to Program $G[x_2^e]$ as a system of 14 equations in the 14 endogenous variables $(\Lambda_1, c_1, x_1^l, x_1^c, x_1^n, x_1^e, c_2, x_2^l, x_2^c, x_2^n, i_1, i_2, S_1^k, S_1^n)$, which is then reduced to a system of seven equations in seven unknowns. Then, using *Mathematica*, we compute the numerical solution paths to Program $G[x_2^e]$ for our calibrated parameter values, and adjust x_2^e so that the QuoL of Generation 3 equals $(1 + \rho)^2\Lambda_1$, implying, as noted above, that the QuoL of Generation t is $(1 + \rho)^{t-1}\Lambda_1$, for all $t \geq 1$. We perform this calculation for three sustained growth rates of the quality of life, namely $\hat{\rho} = 0.00$ (no growth), $\hat{\rho} = 0.01$ and $\hat{\rho} = 0.02$, where $\hat{\rho}$ is the rate of growth of the QuoL expressed in *per annum* terms, with corresponding rates of growth per generation (defined by $\rho = (1+\hat{\rho})^{25}$) equal to $\rho = 0.00$, $\rho = 0.28$ and $\rho = 0.64$, respectively.

4.6. Characteristics of the growth paths

Appendix 5 describes the obtained paths. The first rows in the tables of Appendix 5 display the year-2000 values, repeated in each table to facilitate comparison. Some of the information in the tables of Appendix 5 is reproduced in Tables 3.1-3 and depicted in Figure 3.

The computed paths display the following features.

(1) ***Sustainable quality of life at levels noticeably higher than the year-*2000 *reference level.***

The first column of Table 3.1 gives the QuoL of Generation 1, expressed as a percentage of the year-2000 reference level Λ_0, as a function of the rate of growth.

(2) ***Small tradeoff between the quality of life of the first generation and moderate growth rates.***

The second column of Table 3.1 shows that there is a small tradeoff between the quality of life of the first generation and the rate of growth of the quality of life. Generation 1's sacrifice for the sake of a higher growth rate is extremely small for reasonable growth rates: Generation 1 sacrifices less than 1% (resp. 2%) of QuoL relative to the no-growth QuoL for the sake of a subsequently sustained growth rate of 1% (resp. 2%) per year, which corresponds to 28% (resp. 64%) per generation.

	$\frac{\tilde{\Lambda}_1(\hat{\rho})}{\Lambda_0}$	$\frac{\tilde{\Lambda}_1(0) - \tilde{\Lambda}_1(\hat{\rho})}{\tilde{\Lambda}_1(0)}$
$\hat{\rho} = 0.000$ (No growth)	1.311	0.000
$\hat{\rho} = 0.010$ $\rho = 0.282$	1.300	0.0084 = 0.84%
$\hat{\rho} = 0.020$ $\rho = 0.640$	1.286	0.0192 = 1.92%

Table 3.1. The QuoL of the first generation (first column), and the sacrifice of the first generation to sustain subsequent positive growth rates (second column). The tildes denote the solution for the corresponding variable as a function of $\hat{\rho}$.

(3) ***Large increases in the stock of knowledge, notable increases in physical capital, and moderate increases in consumption and the quality of leisure, while leisure time experiences a slight decrease.***

The increase in the QuoL, despite the worsening of the biosphere (first column of Table 3.2) rests heavily on the increase in knowledge (its steady state value is 2.78 times that of the reference year) and, to a smaller extent, on the increase of physical capital (2.03 times), while consumption and the quality of leisure experience a moderate increase, and leisure time actually goes down slightly.

	Quality of Biosphere	Consumption	Physical Capital	Knowledge	Leisure Time	Quality of Leisure
Year 2000	767.76 - 177.1 = 590.66	23.88	73.65	15.64	0.67	1.40
Steady State	767.76 - 363 = 404.76	31.76	149.26	43.48	0.66	1.82
$\frac{\text{Steady State}}{\text{Year 2000}}$	0.68	1.33	2.03	2.78	0.99	1.30

Table 3.2. Comparison between steady state and year 2000 values for the zero growth path

(4) *Positive sustained growth rates are achieved by transferring resources to education, whereas the fraction of labor devoted to the production of knowledge or output, or to leisure, is not very sensitive to the growth rate.*

	Education $\frac{\tilde{x}_t^e(\hat{\rho})/\tilde{x}_t(\hat{\rho})}{\overline{x}_{2000}^e/\overline{x}_{2000}}$	Output $\frac{\tilde{x}_t^c(\hat{\rho})/\tilde{x}_t(\hat{\rho})}{\overline{x}_{2000}^e/\overline{x}_{2000}}$	Knowledge $\frac{\tilde{x}_t^n(\hat{\rho})/\tilde{x}_t(\hat{\rho})}{\overline{x}_{2000}^n/\overline{x}_{2000}}$	Leisure $\frac{\tilde{x}_t^\ell(\hat{\rho})/\tilde{x}_t(\hat{\rho})}{\overline{x}_{2000}^\ell/\overline{x}_{2000}}$
$\hat{\rho} = 0.00$ (No growth)	0.846	0.994	1.885	0.988
$\hat{\rho} = 0.01$	1.088	0.995	1.998	0.973
$\hat{\rho} = 0.02$	1.395	0.992	2.057	0.957

Table 3.3. Comparison between steady state and year 2000 values of the allocation of labor for the various growth rates. Again, the tildes denote the solution for the corresponding variable as a function of $\hat{\rho}$.

(5) *Slight decrease in leisure time relative to the year 2000 reference values*

As noted above, the fraction of time that Generation *t* devotes to leisure $\frac{x_t^l}{x_t^l + x_t^c + x_t^n + x_t^e}$ turns out to be slightly lower than the year-2000 reference fraction 0.667: see the last column of Table 3.3, where it can also be observed that it actually decreases as the rate of growth increases. This result may be controversial.

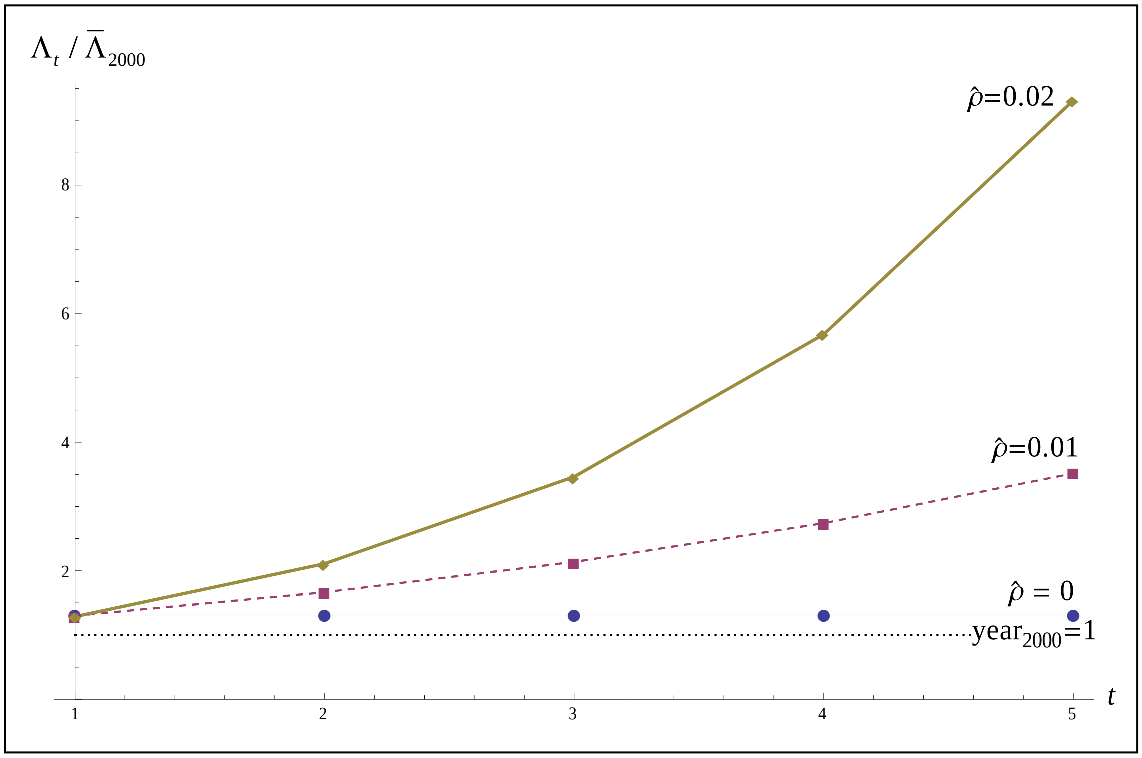

Figure 3.
Paths of quality of life of several generations for alternative rates of growth $\hat{\rho}$
(growth *per annum* in the Quality of Life).
All variables grow at a rate slightly higher than $\hat{\rho}$, with the exception of emissions and the stock of the biosphere, which follow the path described above, with constant low emissions and constant biosphere stock for $t \geq 3$.

5. Introducing uncertainty

A standard form of uncertainty to consider in dynamic models concerns the date at which the human species will end. In this section, we briefly summarize results from our companion paper (Llavador *et al*. 2008) that have a bearing on the analysis in this one.

We work with our benchmark Program SUS. We now suppose that there is a probability p that the world ends at any generation, and that there is an (independent) draw from this random variable at the end of each generation. To model the intergenerational welfare objective, we suppose there is an Ethical Observer (EO) who possesses von Neumann-Morgenstern (vNM) preferences over the lottery that is induced by this random variable. A *prize* is the event that the world lasts exactly T generations. The EO's vNM utility if the world lasts exactly T generations is $W^T(\Lambda_1,...,\Lambda_T) = \min_{1\le t\le T} \Lambda_t$. Thus, if the world were to last forever, the EO's vNM utility would be exactly the solution of Program SUS. Now given the uncertainty about the future existence of the species, the *expected utility* of the EO at an infinite path that generates Qualities of Life $\{\Lambda_1, \Lambda_2, ...\}$ is given by:

$$\sum_{t=1}^{\infty} p(1-p)^{t-1} W^t(\Lambda_1,...,\Lambda_t)\,, \qquad (8)$$

because the probability that the world ends (at the end of) date t is precisely $p(1-p)^{t-1}$.

Consequently, the problem for the EO under uncertainty is to solve Program SUS, but with objective function given by (8). We call this new program, Program Unc-SUS. In our companion paper, we prove the following:

Theorem 3 (Llavador, Roemer & Silvestre, 2008). *If* $(1-p)\hat{k}_4 > 1$*, then the solution to Program Unc-SUS is exactly the solution to Program SUS.* [In particular, Λ_t is constant with respect to *t*.]

If we take 1- $p \geq 0.99$, as does the Stern Review, then with the value of $\hat{k}_4$ we have estimated, the premise of Theorem 3 is true, and so *uncertainty does not matter* for the solution of Program Unc-SUS!

We have not extended Theorem 3 to the more complex models that we have analyzed in this paper, but we conjecture that the analogue of the theorem remains true for those models. The very rough intuition is that the possibilities for growth inherent in a large value of $\hat{k}_4$ more than counteract the discount on the resources allocated to future generations that the EO might contemplate placing, due the possibility that they may not exist, if $(1-p)\hat{k}_4 > 1$.

We further conjecture that the analogue of Theorem 3 will remain true if we allow growth in the QuoL as well.

Therefore, we conjecture that the paths we have computed in this paper would remain the optimal paths, under the kind of uncertainty here postulated.

However, it must be remarked that a more important kind of uncertainty to introduce would be our uncertainty with regard to the physics of global warming. This is a more difficult undertaking.

6. Relation to the literature

The literature offers several approaches that cover some aspects of the issues discussed here from various normative viewpoints. We comment on three of them.

6.1. Sustainability

The sustainability literature initiated in the 1960's emphasizes the destructive effects of economic activity on the environment. "Strong sustainability" advocates bequeathing to future generations a natural environment equivalent to the one that the present generation inherited. "Weak sustainability," on the contrary, only requires "keeping total net investment, suitably defined to encompass all relevant forms of capital, above or equal to zero" (E. Neumayer, 1999, p. 23), admitting a degree of substitutability between natural and produced capital. Both versions tend to advocate a reduction in current consumption in order to alleviate environmental pressure. For instance Kenneth Arrow *et al.* (2004) discuss "genuine investment," a measure of total investment elaborated on a country-by-country basis by the World Bank in the spirit of the weak sustainability criterion, and conclude that "we find reason to be concerned that consumption is excessive."

The sustainability literature focuses on maintaining the capability for human welfare (Neumayer, 1999, p. 20), but does not explicitly deal with future paths of the economic variables or of the standard of living.

6.2. Nordhaus's optimization

Nordhaus (2008a,b) proposes particular paths for CO_2 emissions, CO_2 concentrations and consumption per capita based on an optimization program with objective function

$$\sum_{t=1}^{T} L_t \frac{1}{1-\eta}(c_t)^{1-\eta} \frac{1}{(1+\delta)^t} \quad , \qquad (9)$$

where L_t is the number of people in generation t.[13] He calls the δ and η of (9) "central" and "unobserved normative parameters," reflecting "the relative importance of the different generations." (Nordhaus 2008a, p. 33, 60). Note that the maximin objective function of our Section 2.2 above could be viewed as a limit case of (9) for $L_t = 1$, $\delta = 0$ and $\eta \to \infty$. Nordhaus (2008a) chooses $\eta = 2$ and $\delta = (0.015)^{10}$, corresponding to a per year rate of $\hat{\delta} = 0.015$.[14] Appendix 6 below comments on Nordhaus's (2008a) objective function and on his calibration of its parameters.

The paths for emissions and concentrations proposed as optimal by Nordhaus differ markedly from the ones that we postulate. Figures 4(a) (emissions) and 4(b) (concentrations) illustrate.

Recall that we take as given a conservative path that drops emissions to very low levels by 2050 and stabilizes atmospheric CO_2 concentration at about 450 ppm by 2050. In striking contrast, Nordhaus (2008a, b) proposes as "optimal" a path where emissions and concentrations keep increasing past the end of the 21st century. Nordhaus (2008a, b) proposed values for 2100 are about 11 GtC in emissions, with concentrations at 586.4 ppm at 2100 and at a peak of about 680 ppm at 2180.

In light of the recent climate science research, we view Nordhaus's (2008a, b) "optimal" emission and concentration figures as excessively high, likely to bring about irreversible changes in temperature and unavoidable negative impacts in the welfare of future generations.

On the other hand, our approach does not attempt to find an optimal path of the environmental variables. We adopt instead a path for them which is in line with the recent proposals for stabilization by climate scientists, and we endogenously compute paths for the economic variables aimed at desirable welfare levels for future generations, while following the postulated path for the environmental variables.

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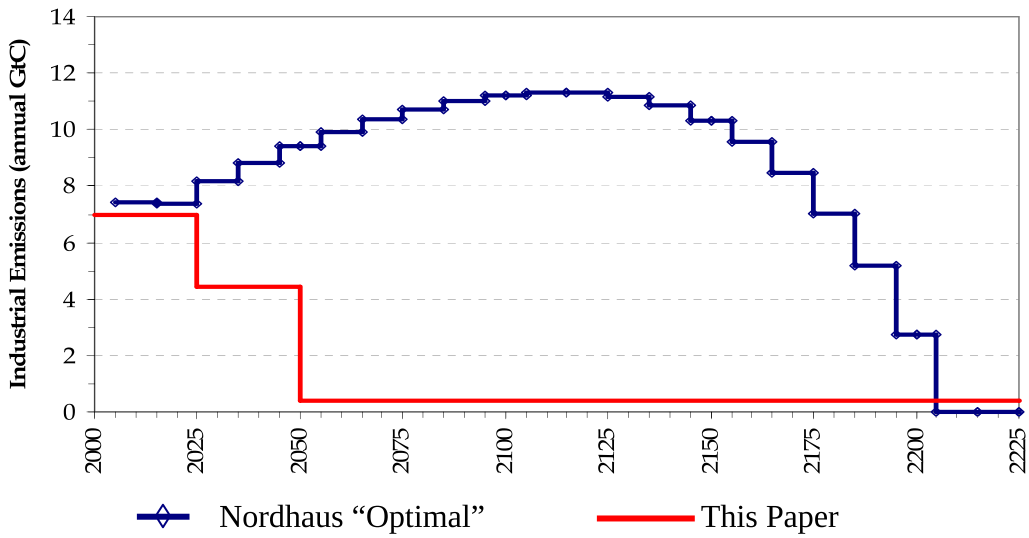
[13] The objective function is given in Nordhaus (2008a, p. 205), with each period $t = 1, 2, \ldots$. understood as a decade (instead of our 25-year generations). His notation is different. The optimization is numerically solved by the General Algebraic Modeling System (GAMS) program, see Nordhaus (2008b).

[14] The latter is half the value adopted in Nordhaus and Boyer (2000), see Nordhaus (2008a, p. 50).

4(a) CO_2 Emissions



4(b) CO_2 Concentrations

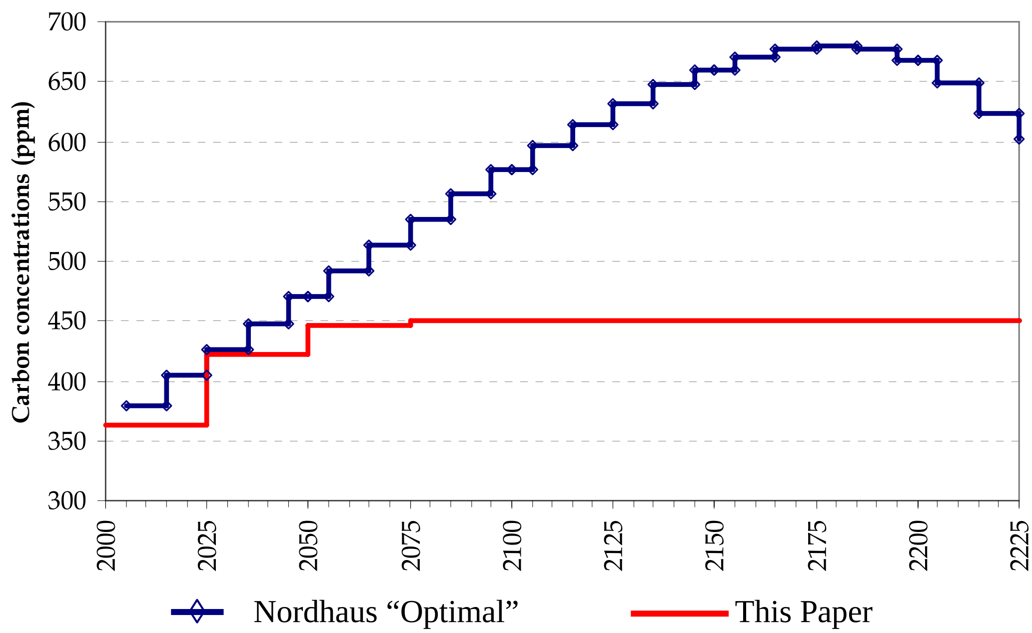


Figure 4.
Comparison of paths for the environmental variables proposed by Nordhaus (2008a,b) with the ones postulated in the present paper.

The paths for Nordhaus "Optimal" are computed by running the program GAMS with data provided in Nordhaus (2008b). The curve labeled "Optimal" of Figure 5-6 in Nordhaus (2008a) displays emissions only for the period 2005-2105, where they coincide with those of Figure 4(a) here (except that there the emissions are per decade, and here per year). Similarly, the curve labeled "Optimal" of Figure 5-7 in Nordhaus (2008a) displays concentrations only for the period 2005-2205, where they coincide with those of Figure 4(b) here.

A striking feature of Nordhaus (2008a) is that the path for per capita consumption (his only variable in the individual utility function) is virtually identical (at least for the 21st century) in the "optimal" and in the "baseline" (*laissez faire*) paths, see his Figure 5.9. Yet he claims (p. 82) that value of the objective function at the "optimal" solution is 3.37 trillions of 2005 US$ higher than at the baseline solution. We conjecture that this puzzle may be partially explained by population growth, which increases the value of the objective function for a given level of consumption per capita, together with minute differences in consumption per capita. Because of the little difference between the optimal and nonoptimal paths of consumption per capita, we conjecture that his rate of growth in consumption per capita is basically driven by his postulated exogenous growth in total factor productivity.

6.3. Cost-Benefit analysis: The Stern Review

Cost-Benefit analysis underpins the recommendations of the Stern Review, in turn based on the reports of the United Nation's Intergovernmental Panel on Climate Change (IPCC 3, 2000) and on Christopher Hope (2006). The Stern Review does not attempt to solve an optimization program: it is rather a cost-benefit analysis arguing that the "costs of inaction are larger than costs of action." Assuming a path of growth for the GDP, and starting from a Business as Usual (*laissez-faire*) hypothesis on the path of GHG emissions, it considers alternative policies that reduce emissions in the present, and eventually stabilize GHG in the atmosphere. The review argues that, properly discounted, the benefits of strong, early action on climate change outweigh the costs.

It should be noted that discount rates have different roles in Cost-Benefit Analysis and discounted-utilitarianism optimization. Discounted utilitarianism (see Section A6.4 below) uses the pure time discount rate δ to weight the utilities of the various generations in the utilitarian maximand, whereas Cost-Benefit Analysis uses the consumption discount rate $\delta + \eta\,\tilde{g}$ to evaluate the changes in future consumption streams due to a particular (marginal) investment project, relative to a reference consumption path that exogenously grows at a rate $\tilde{g}$. The project passes the Cost Benefit test if the discounted sum of the consumption streams is positive.[15] The Stern Review uses a

[15] Writing η and δ here entail some abuse of notation: Compare with (9). The objective function is (Stern, 2007, p. 51), $\int_0^\infty u(c(t))e^{-\delta t}dt$, where $u(c) = \frac{1}{1-\eta}c^{1-\eta}$ ($\eta > 0$; for $\eta = 1$, the expression is $u(c) = \ln c$) is the utility function of generation *t*, and δ is the pure time discount rate above.) Consider a reference consumption stream $\{c(t), t \in [0,\infty)\}$,

pure time discount rate of $\delta = 0.001$ (based on the survival justification), together with $\eta = 1$ and $\tilde{g} = \frac{\dot{c}}{c} = 0.013$ (1.3 % per annum), yielding a *consumption discount rate* of 0.014. Its commentators suggest higher consumption discount rates (Arrow, 2007, Nordhaus, 2007, Martin Weitzman, 2007: see the debate in the *Postscripts to the Stern Review* available at www.sternreview.org.uk, as well as the issue of *World Economics* 7 (4), October-December 2006, and the subsequent Simon Dietz *et al*., 2007).

Because the Stern Review does not solve an optimization program, its recommendations are in principle open to the criticism, voiced by the critics of the Review, that the consumption discount rate should reflect the rates of return of the available investment alternatives: even if, using a consumption discount rate of 0.014, carbon emission reductions pass the Cost-Benefit test, future generations could conceivably be better off if the current generation avoided incurring the costs of GHG reductions and invested instead in other intergenerational public goods. In defense of the Review, Dietz *et al*. (2007, p. 137) argue that "it is hard to know why we should be confident that social rates of return would be, say, 3% or 4% into the future. In particular, if there are strong climate change externalities, then social rates of return on investment may be much lower than the observed private returns on capital over the last century, on which suggestions of a benchmark of 3% or 4% appear to be based."

Our approach is in a sense dual to Cost-Benefit analysis. The latter takes as given a path for the economic variables, and recommends a path for the environmental variables (based on a cost-benefit criterion in the spirit of discounted utilitarianism). We, on the contrary, take as given a path for the environmental variables, and recommend paths for the economic variables (based on the human sustainability and human development criteria).

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that grows at rate $\tilde{g}$, with $c(0) = 1$, and a "small" project that will modify the consumption stream by $\{\Delta c(t), t \in [0,\infty)\}$. Up to a first-order approximation, the change in the value of the objective function is $\int_0^\infty u'(c(t))\Delta c(t)e^{-\delta t}dt = \int_0^\infty c(t)^{-\eta}\Delta c(t)e^{-\delta t}dt = \int_0^\infty (e^{\tilde{g}t})^{-\eta}\Delta c(t)e^{-\delta t}dt = \int_0^\infty e^{-(\eta\tilde{g}+\delta)t}\Delta c(t)dt$, i. e., the discount rate on consumption, defined as the relative change in the discount factor, is $\eta\tilde{g} + \delta$. The project passes the cost-benefit test if $\int_0^\infty e^{-(\eta\tilde{g}+\delta)t}\Delta c(t)dt > 0$.

7. Summary and conclusions

Our starting point has been a notion of human quality of life, in the spirit of the human development index (HDI), that avoids the consumptionist fallacy by emphasizing three other factors:

(i) Education, which modifies the value of leisure time to the individual, in addition to enhancing her productivity;

(ii) Knowledge, in the form of culture and science, which directly improves the living experience, in addition to raising total factor productivity; and

(iii) The quality of the environment.

Because of the importance of climate change, we interpret the environmental variable as the concentration of greenhouse gases (GHG) in the atmosphere. We exogenously specify a path of emissions and associated GHG concentration that climate scientists believe to be physically feasible yielding a stabilized concentration of atmospheric GHG. In line with the consensus expressed in the various IPCC reports and emphasized in the Stern Review, we hypothesize a "catastrophic" level of GHG such that the quality of life tends to zero as the GHG stock approaches this level. We quantify the quality of the environment as the difference between the catastrophic and actual levels.

We adopt social objectives based either on an intergenerational version of the maximin criterion, or on the valuation of sustained human development as a public good. In the first case, the optimization program maximizes the quality of life that can be sustained for all generations. In the second case, we maximize the quality of life of the first generation subject to achieving a given, constant rate of growth for all subsequent generations: this we call the Human Development Optimization Program. These objectives stand in sharp contrast to the conventional criterion of maximizing the discounted sum of utilities, which we find ethically unjustifiable, at least for the discount factors typically used.

Ideally, for the Maximin Program, we would like to approach paths where all variables are stationary, whereas for the Human Development Optimization Program we would like to approach balanced-growth paths, where all variables grow at the same rate. But the stock of GHG cannot grow without bound, because an upper bound is imposed by the catastrophic level. Accordingly, our computations fix emissions and the stock of the public bad so that the stock is stabilized after two generations.

The resulting dynamic optimization programs defy explicit analytical solutions, and our approach has been computational. As a benchmark, we have considered a simple growth model with physical and human capital (but no environmental or knowledge stocks) and proved a turnpike theorem for it. We have then devised computational algorithms inspired by the turnpike property for constructing feasible and desirable, although not necessarily optimal, paths in the more complex and interesting models.

We have adopted a simplified path for emissions and the stock of the biosphere that is based on the more elaborate paths proposed in the IPCC 2007 report aiming at stabilizing the concentration of CO_2 in the atmosphere at 450 ppm (363 in our units). Our simplified version assumes that we jump to a steady state in two generations, after which emissions are maintained at a very low level and the concentration of CO_2 in the atmosphere is stabilized. We have then computed solutions for the economic variables, by an algorithm that mimics the turnpike method.

The main qualitative conclusions of our computations are that it is possible to sustain quality of life levels higher than the year 2000 reference value, even when maintaining a positive rate of growth for all successive generations. Not surprisingly, higher rates of sustained growth require a lower QuoL for the first generation, but the tradeoff is small, and the first generation reaches a QuoL higher than the reference value for reasonable rates of growth.

Achieving this kind of human sustainability under the postulated environmental path requires particular kinds of behavior for the economic variables. In particular, the economy should invest heavily in knowledge, and also, to a lesser extent, in physical capital. Consumption and the quality of leisure should experience a moderate increase, while leisure time slightly decreases. Positive sustained growth rates require the transfer of resources to education, whereas the allocation of labor to the production of knowledge or output, or to leisure, is not very sensitive to the growth rate postulated.

Our analysis departs from the literature in three dimensions: (a) the concept of the quality of life, (b) social welfare criteria, and (c) method. For (a), we avoid the consumptionist fallacy by considering that the quality of life is affected by knowledge, the environment and educated leisure. For (b), we consider both a maximin (or human sustainability) criterion, and a human development criterion, where we fix positive rates of growth with the justification than human development has the character of a public good. As for (c), our method in this paper is inspired by optimization, but, given the current uncertainties in climate science, we do not attempt to compute an optimal path for environmental variables: we take instead as given a conservative path for the environmental variables, and propose paths for the economic variables based on the human sustainability and human development criteria.

APPENDIX 1. THE TURNPIKE THEOREM

A1.1. The program

Recall that we aim at finding the maximum level or sustainable quality of life for a fairly simple infinitely lived economy. Formally:

Program SUS

$\max \Lambda \quad s.t.$

$(P1) \quad c_t^{\alpha}(x_t^l)^{1-\alpha} \geq \Lambda, \quad t \geq 1,$

$(P2) \quad \hat{k}_4 x_{t-1}^e \geq x_t^e + x_t^l + x_t^c, \quad t \geq 1,$

$(P3) \quad \hat{k}_2 (S_t^k)^{\theta} (x_t^c)^{1-\theta} \geq c_t + i_t, \quad t \geq 1,$

$(P4) \quad (1-\tilde{\delta}) S_{t-1}^k + i_t \geq S_t^k, \quad t \geq 1.$

The initial endowment is a vector (x_0^e, S_0^k).

The *value function* of the program maps the initial endowment into the value Λ; thus we write $V(x_0^e, S_0^k) = \Lambda$.

Define $E^{\Lambda} = \{(x_0^e, S_0^k) | V(x_0^e, S_0^k) = \Lambda\}$. This is the set of initial endowments that generate the same value for SUS.

We define a *feasible path* as a set of sequences $\{x_t^e\}_{t=0,1,2....}, \{S_t^k\}_{t=0,1,2....}$ and all other variables beginning at $t = 1$, such that inequalities (P2), (P3), and (P4) hold. Denote the set of feasible paths by $\mathscr{P}$.

Denote the set of feasible paths beginning at a given initial vector (x_0^e, S_0^k) by $P(x_0^e, S_0^k)$.

Proposition 1. *The set* $\mathscr{P}$ *is a closed convex cone. The set* $P(x_0^e, S_0^k)$ *is closed and convex.*

Proposition 2. *At the solution to Program SUS, all the constraints* (P1)-(P4) *bind at all dates*.

Proposition 3. A. *Let* $(\tilde{x}_0^e, \tilde{S}_0^k) > (x_0^e, S_0^k)$. *Then* $V(\tilde{x}_0^e, \tilde{S}_0^k) > V(x_0^e, S_0^k)$.

B. *Along the optimal path beginning at* (x_0^e, S_0^k), *there is no T such that* $(x_T^e, S_T^k) > (x_0^e, S_0^k)$.

C. *Let* $\{(x_{0j}^e, S_{0j}^k) \in E^{\kappa}\}$ *be an infinite sequence of points in* E^{κ}, *some fixed* κ, *such that* $x_{0j}^e \to \infty$. *Then* $S_{0j}^k \to 0$.

Proof.

A. If $(\tilde{x}_0^e, \tilde{S}_0^k) > (x_0^e, S_0^k)$, then there is a positive number δ^* such that $(x_T^e, S_T^k) > (1+\delta^*)(x_0^e, S_0^k)$. Since $\mathscr{P}$ is a cone, and the quality of life of Generation *t* is homogenous of degree 1 in its arguments, it follows immediately that $V(\tilde{x}_0^e, \tilde{S}_0^k) > (1+\delta^*)V(x_0^e, S_0^k)$.

B. Suppose that there is a *T* such that $(x_T^e, S_T^k) > (x_0^e, S_0^k)$. Let the value of the program be κ. By Part A, the value of the sub-program *that begins at date T* is strictly greater than κ. This contradicts the fact that the constraints (P1) are binding for all *t*.

C. Suppose the premise were false; then there is a subsequence $S_{0\,j}^k \to S > 0$, some *S*. We can choose a number $\hat{S} > S$ and a number $\hat{x}$ such that $V(\hat{x}, \hat{S}) = \hat{\kappa} > \kappa$. We can also choose an index *j* such that the program beginning with the endowments $(x_{0\,j}^e, S_{0\,j}^k)$ possesses a feasible path that, at its first step, has three properties:

(i) $S_1^k > \hat{S}$,

(ii) $x_1^e > \hat{x}$,

(iii) $c_1^\alpha (x_1^l)^{1-\alpha} > \hat{\kappa}$.

(This is obvious from examining the technology.) It therefore follows that $V(x_1^e, S_1^k) > \hat{\kappa}$: invoke Part A of this proposition. But this is a contradiction, because $V(x_{0\,j}^k, S_{0\,j}^k) = \kappa < \hat{\kappa}$. ■

Since all the constraints of SUS bind, we can write down the Kuhn-Tucker conditions for this concave program. It turns out that these conditions imply only three new pieces of information, which are:

(D1) $\dfrac{x_t^l}{c_t} = \dfrac{1-\alpha}{\alpha(1-\theta)} \dfrac{x_t^c}{c_t + i_t}$ for all $t \geq 1$;

(D2) $\dfrac{x_{t+1}^l}{c_{t+1}} = \dfrac{x_t^l}{c_t} \dfrac{\hat{k}_4}{1-\tilde{\delta}} \left(1 - \dfrac{\theta(c_t + i_t)}{S_t^k}\right), \quad t \geq 1.$

(D3) $\sum_t (\dfrac{1}{\hat{k}_4})^t x_t^l$ converges.

The other Kuhn-Tucker conditions just define the various Lagrangian multipliers, which are all non-negative.

It follows that: *A feasible path and a number* κ *for which all the primal constraints bind at all t, and for which (D1) ,(D2) and (D3) hold, is an optimal solution.*[16]

A1.2. The stationary ray

We ask: Is there a ray of initial endowments in $\Re^2_+$ for which the optimal solution is *stationary*, that is, for which all variables are constant over time? We study this by writing down the primal constraints and equations (D1) and (D2) for a hypothetical stationary ray, and see what they imply. Indeed, we can solve them: there is a unique such ray for the initial condition. The ray passes through the following point:

$$x_0^e = 1, \quad S_0^k = (\hat{k}_4 - 1)\left(\frac{\hat{k}_2\hat{k}_4\theta}{\hat{k}_4 + \tilde{\delta} - 1}\right)^{\frac{1}{1-\theta}} x^c*, \quad \text{where } x^c* = \frac{\alpha(1-\theta)(\hat{k}_4 + \tilde{\delta} - 1)}{\alpha(1-\theta)(\hat{k}_4 + \tilde{\delta} - 1) + (1-\alpha)(\hat{k}_4 + \tilde{\delta} - 1 - \hat{k}_4\delta\theta)}.$$

Indeed, we can compute the values of all the variables on this ray. Call these the *stationary state values.* Of course they are defined up to a multiplicative constant. Let us denote this ray by $\hat{\Gamma}$.

A1.3. The turnpike theorem

It is very difficult to actually compute the optimal path, if we begin from an endowment vector off the stationary ray $\hat{\Gamma}$. We shall, however, prove:

Proposition 4. *From any initial vector* (x_0^e, S_0^k), *the optimal solution to SUS converges to a point on* $\hat{\Gamma}$.

In the following, given any two variables a_t and b_t, we use the notation for ratios: $\frac{a_t}{b_t} = \left(\frac{a}{b}\right)_t$.

The proof proceeds in the following steps.

Lemma. *Suppose, in the optimal solution, the limit of the sequence* $\{(\frac{x^l}{c})_{t=1,2,...}\}$ *exists and is finite. Then the solution converges to the stationary state values.*

Proof.

[16] One may ask, conversely: Does the optimal solution have to satisfy these equations? The answer to this must be affirmative: there is an infinite dimensional version of the Kuhn-Tucker theorem, using the Hahn-Banach theorem, which tells us that this is so.

1. Denote the limit of the sequence $\{(\frac{x^l}{c})_{t=1,2,...}\}$ by $\bar{\lambda}$. We first argue that $\bar{\lambda} \neq 0$. If $\bar{\lambda} = 0$, then $\lim\left(\frac{c}{x^l}\right)_t = \infty$. By (D1), $\lim\left(\frac{x^c}{c+i}\right)_t = 0,$ and so $\lim\left(\frac{x^c}{S^k}\right)_t = 0$, by invoking (P3). Now $\frac{\theta(c_t + i_t)}{S_t^k} = \theta\hat{k}_2\left(\frac{x_t^c}{S_t^k}\right)^{1-\theta}$, so $\lim\frac{\theta(c_t + i_t)}{S_t^k} = 0$, which means, by (D2), that $\frac{(c/x^l)_{t+1}}{(c/x^l)_t} \to \frac{1-\tilde{\delta}}{\hat{k}_4} < 1$, because $\hat{k}_4 > 1$. It is therefore impossible that $\lim\left(\frac{c}{x^l}\right)_t = \infty$. Therefore $\bar{\lambda} > 0$.

2. By (P1), $x_t^l\left(\frac{c_t}{x_t^l}\right)^{\alpha} = \kappa$ for all *t*. Therefore $\lim x_t^l = \kappa\bar{\lambda}^{\alpha}$ and so $\lim c_t = \kappa\bar{\lambda}^{\alpha-1}$. From (D2), it also follows that $\frac{\hat{k}_4}{1-\delta}\lim(1-\frac{\theta(c_t + i_t)}{S_t^k}) = 1$; therefore $\lim(\frac{c+i}{S^k})_t$ has the value of the ratio of $(c+i)/S^k$ in the stationary state. Therefore $\lim\left(\frac{x^c}{S^k}\right)_t$ has the same value as the ratio of those variables in the stationary state. By (D1) it now follows that $\bar{\lambda}$ is also the ratio of x^l / c in the stationary state.

3. Suppose that there were a subsequence of $\{S_t^k\}$ that diverged to infinity. Since $\lim\left(\frac{x^c}{S^k}\right)_t$ is finite, it follows that the same subsequence of $\{x_t^c\}$ diverges to infinity. It follows from (P2) that the same subsequence of $\{x_t^e\}$ diverges to infinity. In particular, there exists a *T* such that $(x_T^e, S_T^k) > (x_0^e, S_0^k)$. But this contradicts Part B of Proposition 3. Therefore the sequence $\{S_t^k\}$ is bounded. It immediately follows that the sequence $\{x_t^c\}$ is bounded, since $\lim\left(\frac{x^c}{S^k}\right)_t$ exists and is finite; and since $\lim(\frac{c+i}{S^k})_t$ also exists and is finite, the sequence $\{i_t\}$ is bounded.

Thus all the sequences of variables, except possibly for $\{x_t^e\}$, are bounded. Therefore we can choose a single subsequence of all the variables (except possibly of $\{x_t^e\}$) which *converge* to values $(\bar{S}^k, \bar{x}^c, \bar{i})$ and we have already shown that $\{x_t^l\}, \{c_t\}$ converge to values $\bar{x}^l$ and $\bar{c}$.

Furthermore we know that $\{S_t^k\}$ converges to a positive number, because $\lim(\frac{\theta(c_t+i_t)}{S_t^k})$ has the value of the same ratio in the stationary state and $\{c_t\}$ converges to a positive number.

It now follows, by invoking Proposition 3, Part C, that $\{x_t^e\}$ does not diverge to infinity – since $(x_t^e, S_t^k) \in E^k$ for all *t*. So there is a subsequence of the original sequence such that *all* variables converge.

We proceed to show that this subsequence of variables converges to stationary state values. Denote the limits:

$$\overline{\lambda}_1 = \lim \frac{c_t + i_t}{x_t^c} = \lim \frac{\overline{c} + i_t}{x_t^c}, \quad (a)$$

$$\overline{\lambda}_2 = \lim(\frac{S^k}{x^c})_t. \qquad (b)$$

We have shown that $\overline{\lambda}_1$ and $\overline{\lambda}_2$ are the values of the corresponding ratios in the stationary state. Now from (P3) we have:

$$\hat{k}_2 x_t^c \overline{\lambda}_2^\theta - i_t \to \overline{c} \qquad \text{(c)}$$

Note that equations (a) and (c) comprise two simultaneous equations, in the limit, for the limits of the variables x^c and *i*. Hence the sequences $\{x_t^c\}$ and $\{i_t\}$ must converge, and to stationary state values, since these same two equations hold for the stationary state variables. We therefore have, by (b), that $\{S_t^k\}$ also converges to the appropriate stationary state value. Likewise with $\{x_t^e\}$.

Finally, indeed the *whole* sequence of variables converges to the same stationary state: for if not, there would be another limit point approached simultaneously by some other subsequence of the variables, to a stationary state. But since the stationary ray is unique, that limit of (x_t^e, S_t^k) must also be on the ray $\hat{\Gamma}$. However, we cannot have two subsequences approaching different points on the ray: that would violate Proposition 3, Part B. ■

Proof of Proposition 4 [17].

Step 1. On the optimal path, the sequence $\{(\frac{x^l}{c})_{t=1,2,...}\}$ does not diverge to infinity.

[17] Thanks to Cong Huang, who completed and simplified this proof.

Suppose it did diverge to infinity. Then from (D1), the sequence $\frac{x_t^c}{c_t + i_t}$ diverges to infinity also. But, invoking (P3), $\frac{x_t^c}{c_t + i_t} = \left(\frac{x_t^c}{\hat{k}_2 S_t^k}\right)^{\theta}$, and so $\frac{x_t^c}{S_t^k} \rightarrow \infty$. Now $\frac{\theta(c_t + i_t)}{S_t^k} = \theta\hat{k}_2\left(\frac{x_t^c}{S_t^k}\right)^{1-\theta}$ and so it follows that $\frac{\theta(c_t + i_t)}{S_t^k}$ diverges to infinity. But this contradicts (D2), for it would mean that eventually the ratio $\frac{x_t^l}{c_t}$ is negative.

Step 2. Hence it follows that on the optimal path, the sequence $\{(\frac{x^l}{c})_{t=1,2,...}\}$ has a (finite) limit point. If the sequence $\{(\frac{x^l}{c})_{t=1,2,...}\}$ indeed converges to this limit point, then the theorem is proved, by the Lemma.

Step 3. Thus, the remainder of the proof will show that the limit point of the sequence $\{(\frac{x^l}{c})_{t=1,2,...}\}$ is unique, and hence it is the limit of the sequence.

By exploiting equations (D1) and (P3), we can rewrite (D2) as follows:

(D2*) $$\left(\frac{x^l}{c}\right)_{t+1} = \left(\frac{x^l}{c}\right)_t \frac{\hat{k}_4}{1-\tilde{\delta}}\left(1 - \theta\hat{k}_2\left(\frac{\hat{k}_2\alpha(1-\theta)}{1-\alpha}\right)^{\frac{1-\theta}{\theta}}\left(\frac{x^l}{c}\right)_t^{\frac{1-\theta}{\theta}}\right).$$

It will be convenient to define the function: $f^*(x) = ax(1 - bx^r)$,

where $a = \frac{\hat{k}_4}{1-\delta}$, $b = \theta\hat{k}_2\left(\frac{\hat{k}_2\alpha(1-\theta)}{1-\alpha}\right)^{\frac{1-\theta}{\theta}}$, and $r = (1-\theta)/\theta$. Thus (D2*) says that

$$f^*\left(\frac{x_t^c}{c_t}\right) = \frac{x_{t+1}^c}{c_{t+1}} \text{ for all } t.$$

Compute that $\frac{d^2 f^*}{dx^2} = -rab(1+r)x^{r-1}$, and so f^* is a concave function on $\Re_+$. Let A^* be the value of the ratio $\frac{x^l}{c}$ in the stationary state. Then we have: $f^*(A^*) = A^*$ and $f^*(0) = 0$. The first claim follows since the equation (D2*) holds, of course, at the stationary state as well.

Finally, note that another root of f^* is given by $x^* = (1/b)^{1/r}$. Concavity implies that f^* has only the two fixed points 0 and A^*.

Because $\{(\frac{x^l}{c})_{t=1,2,...}\}$ is bounded, it possesses a lim inf and a lim sup. For convenience, denote $y_t = \left(\frac{x^l}{c}\right)_t$, and define

$$\sigma = \liminf y_t, \quad \sigma^* = \limsup y_t .$$

Since $f^*(y_t) = y_{t+1}$, we have $\inf f^*(y_t) = \sigma$, and by continuity of f^*, $\inf f^*(y_t) = f^*(\inf y_t) = f^*(\sigma) = \sigma$, so σ is a fixed point of f^*. In like manner, σ^* is a fixed point of f^*.

If we can establish that $\sigma \neq 0$, then we must have $\sigma = A^* = \sigma^*$, and hence the limit of $\{y_t\}$ exists. But this is established by an argument that mimics Step 1 of the proof of the lemma, as follows.

If $\sigma = 0$ then, by (D1), $\liminf \left(\frac{x^c}{c+i}\right)_t = 0$, and so $\liminf \left(\frac{x^c}{S^k}\right)_t = 0$, by invoking (P3). Now $\frac{\theta(c_t + i_t)}{S_t^k} = \theta \hat{k}_2 \left(\frac{x_t^c}{S_t^k}\right)^{1-\theta}$, so $\liminf \frac{\theta(c_t + i_t)}{S_t^k} = 0$, which means, by (D2), that $\liminf \frac{y_{t+1}}{y_t} = \frac{\hat{k}_4}{1-\tilde{\delta}} > 1$, because $\hat{k}_4 > 1$. But this immediately implies that $\liminf y_t > 0$, a contradiction. Therefore $\sigma = 0$, and Proposition 4 is proved. ■

The proof of Theorem 1 follows from the previous discussion, in particular from A2 and Proposition 4. ■

APPENDIX 2. BALANCED GROWTH PATHS IN PROGRAM *E*

A2.1. The program

We write down the optimization program for Model *E* where we assume that emissions and the stock of the biosphere are fixed at levels e^* and S^m*, respectively.

max Λ subject to

$$(\lambda_t) \quad c_t^{\alpha_c}(x_t^{\ell})^{\alpha_\ell}(S_t^n)^{\alpha_n}(\hat{S}^m - S^m*)^{\alpha_m} \geq \Lambda(1+\rho)^{t-1}, \text{ for } t \geq 1,$$

$$(y_t) \quad k_{11}(S^{m*})^{\theta_m}(e^*)^{\theta_e}(x_t^c)^{\theta_c}(S_t^k)^{\theta_k}(S_t^n)^{\theta_n} \geq c_t + i_t, t \geq 1,$$

$$(w_t) \quad (1-\delta^k)S_{t-1}^k + k_5 i_t \geq S_t^k, t \geq 1,$$

$$(n_t) \quad (1-\delta^n)S_{t-1}^n + k_2 x_t^n \geq S_t^n, t \geq 1,$$

$$(p_t) \quad k_4 x_{t-1}^e \geq x_t^e + x_t^n + x_t^{\ell} + x_t^c, t \geq 1.$$

The Lagrangian multipliers have been written to the left of the constraints. Our problem is to find the condition on the endowment vector (x_0^e, S_0^k, S_0^n) such that the optimal solution to the program is a path of steady growth. At steady-state growth there will be three different growth rates:

- the variables $S_t^n, x_t^n, x_t^e, x_t^c, x_t^l$ will grow at a rate g
- the variables S_t^k, i_t, c_t will grow at a rate γ
- Λ_t will grow at a rate ρ.

From the production function, we must have:

$$(1+\gamma) = (1+g)^{\theta_c}(1+\gamma)^{\theta_k}(1+g)^{\theta_n}.$$

However, as we have chosen parameters so that $1-\theta_k = \theta_c + \theta_n$, we have $\gamma = g$, and so there will be only two growth rates, namely g and ρ. From the first constraint, we must have:

$$(1+g)^{\alpha_c+\alpha_\ell+\alpha_n} = 1+\rho;$$

thus a chosen rate g determines ρ.

Given the ordered triple (g, e^*, S^{m*}), there will be a ray $\Gamma(g, e^*, S^{m*}) \subset \Re^3_+$ such that if the endowment vector $(x^e_0, S^n_0, S^k_0) \in \Gamma(g, e^*, S^{m*})$, then balanced growth at rates g (and ρ) will occur at the optimal solution to the program. We proceed to determine this ray.

To do so, we first derive the Kuhn-Tucker conditions for the program, which are:

$$(a)\ (\partial\Lambda) \quad 1-\sum_{t=1}^{\infty}\lambda_t(1+\rho)^{t-1}=0, t\geq 1,$$

$$(b)\ (\partial x^e_t) \quad k_4 p_{t+1}-p_t=0 \Rightarrow p_t=(1/k_4)^{t-1}p_1, t\geq 1,$$

$$(c)\ (\partial x^\ell_t) \quad \frac{\lambda_t\alpha_\ell\Lambda(1+\rho)^{t-1}}{x^\ell_t}-p_t=0, t\geq 1,$$

$$(d)\ (\partial x^n_t) \quad k_2 n_t = p_t, t\geq 1,$$

$$(e)\ (\partial x^c_t) \quad \frac{y_t\theta_c(c_t+i_t)}{x^c_t}-p_t=0, t\geq 1,$$

$$(f)\ (\partial c_t) \quad \lambda_t\frac{\alpha_c\Lambda(1+\rho)^{t-1}}{c_t}-y_t=0, t\geq 1,$$

$$(g)\ (\partial i_t) \quad -y_t+k_5 w_t=0, t\geq 1,$$

$$(h)\ (\partial S^k_t) \quad \frac{y_t\theta_k(c_t+i_t)}{S^k_t}-w_t+(1-\delta^k)w_{t+1}=0, t\geq 1,$$

$$(i)\ (\partial S^n_t) \quad \frac{\lambda_t\alpha_n\Lambda(1+\rho)^{t-1}}{S^n_t}+\frac{y_t\theta_n(c_t+i_t)}{S^n_t}+(1-\delta^n)n_{t+1}-n_t=0, t\geq 1.$$

We now substitute into these equations the variable values on a balanced growth path.

1. (b) and (c) imply that:

$$\lambda_t=\left(\frac{p_1x^\ell_1}{\alpha_\ell\Lambda}\right)\left(\frac{1+g}{k_4(1+\rho)}\right)^{t-1}.$$

2. By (a) it follows that $1=\left[\sum_{t=1}^{\infty}(\frac{1+g}{k_4})^{t-1}\right]\frac{p_1x^\ell_1}{\alpha_\ell\Lambda}$. This defines p_1 at the solution, and hence p_t. Note that p_1 will be defined as long as $k_4>1+g$, so that the series converges. It follows that :

$$1=\left(\frac{p_1x^\ell_1}{\alpha_\ell\Lambda}\right)\frac{k_4}{k_4-(1+g)}.$$

3. (d) defines $n_t=p_t/k_2=\frac{p_1}{k_2}(1/k_4)^{t-1}$.

(e) defines $y_t\geq 0$; (g) defines $w_t=y_t/k_5$. Thus all the dual variables are defined and non-negative.

This leaves equations (h), (f) and (i) which we now analyze.

4. <u>Analysis of (h)</u>

(e) implies $y_t = \frac{p_t x_t^c}{\theta_c (c_t + i_t)}$ so (h) says $\frac{p_t x_t^c \theta_k}{\theta_c S_t^k} = \frac{y_t - (1-\delta^k) y_{t+1}}{k_5}$. Substituting for y_t, and multiplying by $\frac{\theta_c}{p_t}$ gives:

$$\frac{k_5 x_t^c \theta_k}{S_t^k} = \frac{x_t^c}{c_t + i_t} - \frac{1-\delta^k}{k_4} \frac{x_{t+1}^c}{c_{t+1} + i_{t+1}};$$

which, using the balanced growth property of the path means:

$$\frac{k_5 x_1^c \theta_k}{S_0^k (1+g)} = \frac{x_1^c}{c_1 + i_1} - \frac{1-\delta^k}{k_4} \frac{x_1^c}{c_1 + i_1}.$$

Multiplying by $\frac{1+g}{x_1^c}$, we have:

(A) $$\frac{k_5 \theta_k}{S_0^k} = \frac{(1+g)(1 - (\frac{1-\delta^k}{k_4}))}{c_1 + i_1}.$$

5. <u>Analysis of (f)</u>

(f) implies $\frac{\lambda_t \alpha_c \Lambda (1+\rho)^{t-1}}{c_t} = \frac{p_t x_t^c}{\theta_c (c_t + i_t)}$ which may be reduced to the equation:

(B) $$\frac{x_1^{\ell}}{\alpha_{\ell}} = \frac{c_1 x_1^c}{\alpha_c \theta_c (c_1 + i_1)}.$$

6. <u>Analysis of (i)</u>

We express λ_t, y_t, n_t in terms of p_t; after some algebraic manipulation (i) reduces to:

(C) $$\frac{\alpha_n x_1^{\ell}}{\alpha_{\ell}(1+g) S_0^n} + \frac{\theta_n x_1^c}{\theta_c (1+g) S_0^n} + \frac{1}{k_2}\left(\frac{1-\delta^n}{k_4} - 1\right) = 0.$$

In sum, we have the three equations (A), (B), and (C). From the primal constraints we have:

(D) $k_{11}(1+g)^{\theta_n + \theta_k} (S_0^k)^{\theta_k} (S_0^n)^{\theta_n} (x_1^c)^{\theta_c} (S^m{*})^{\theta_m} (e^*)^{\theta_e} = c_1 + i_1$,

(E) $x_0^e (k_4 - (1+g)) = x_1^n + x_1^c + x_1^{\ell}$,

(F) $k_5 i_1 = S_0^k (g + \delta^k)$,

(G) $k_2 x_1^n = (g + \delta^n) S_0^n$.

Define the following expressions:

$$v^n(g) = \frac{\delta^n + g}{k_2},$$

$$p^i(g) = \frac{\delta^k + g}{k_5},$$

$$p^c(g) = \left(1 - \frac{1-\delta^k}{k_4}\right)\frac{1+g}{k_5\,\theta_k} - \frac{\delta^k + g}{k_5},$$

$$v^l(g) = \left(1 - \frac{1-\delta^n}{k_4}\right)\frac{\alpha_l}{k_2}\frac{p^c(g)}{\alpha_c\theta_n\left(p^c(g) + p^i(g)\right) + \alpha_n p^c(g)}\left(1+g\right),$$

$$v^c(g) = \left(1 - \frac{1-\delta^n}{k_4}\right)\frac{\alpha_c\,\theta_c}{k_2}\frac{p^c(g) + p^i(g)}{\alpha_c\theta_n\left(p^c(g) + p^i(g)\right) + \alpha_n p^c(g)}\left(1+g\right),$$

$$q^n(g) = \frac{k_4 - \left(1+g\right)}{v^n(g) + v^l(g) + v^c(g)},$$

and $q^k\left(g, e^*, S^{m*}\right) = \left(\frac{k_{11}\left(v^c(g)\right)^{\theta_c}}{p^c(g) + p^i(g)}\right)^{\frac{1}{\theta_n+\theta_c}} (1+g)^{\frac{\theta_n+\theta_k}{\theta_n+\theta_c}} \cdot q^n(g) \cdot (e*)^{\frac{\theta_e}{\theta_n+\theta_c}} \cdot \left(S^{m*}\right)^{\frac{\theta_m}{\theta_n+\theta_c}}$.

Now from (F) we solve for i:

$$i_1 = p^i(g) S_0^k.$$

From (G), we have

$$x_1^n = v^n(g) S_0^n.$$

From (A) and the above expression for i_1, we have:

$$c_1 = p^c(g) S_0^k.$$

Now view (B) and (C) as a pair of simultaneous linear equations in (x_1^c, x_1^l). Solving them gives

$$(x_1^c, x_1^l) = (\nu^c(g), \nu^l(g)) S_0^n.$$

Substituting these values into (E) gives

$$S_0^n = q^n(g)x_0^e .$$

Finally, we obtain

$$S_0^k = q^k(g, e^*, S^{m*})x_0^e$$

by substituting $S_0^n = q^n(g)x_0^e$ and $x^c = \nu^c(g)q^n(g)x_0^e$ into equation (D) and solving for S_0^k.

Statement (ii) of Theorem 2 is immediately derived from the above equations. Statement (i) asserts that the endowments grow along the ray $\Gamma(g, e^*, S^{m*})$ at rate 1 + *g*, and statement (iii) says that all flow variables exhibit balanced growth. ■

APPENDIX 3. REACHING THE RAY $\Gamma(g, e^*, S^{m*})$ IN TWO GENERATIONS FROM DATE-2000 ENDOWMENTS

The ray $\Gamma(g, e^*, S^{m*})$ is defined by

$$\Gamma(g, e^*, S^{m*}) = \{(x^e, S^k, S^n) \in \Re_+^3 : S^k = q^k(g, e^*, S^{m*})x^e, S^n = q^n(g)x^e\},$$

where the coefficients q^n and q^k have been computed in Appendix 2 above.

<u>Program</u> $G[x_2^e]$: *G*iven $(\rho, e_1, S_1^m, e_2, S_2^m, e^*, S^{m*})$ and x_2^e, Max Λ_1 subject to

(A3.1) $(\mu_1) : (c_1)^{\alpha_c}(x_1^l)^{\alpha_l}(S_1^n)^{\alpha_n}(\hat{S}^m - S_1^m)^{\alpha_m} \geq \Lambda_1,$

(A3.2) $(\mu_2) : (c_2)^{\alpha_c}(x_2^l)^{\alpha_l}(q^n(g)x_2^e)^{\alpha_n}(\hat{S}^m - S_2^m)^{\alpha_m} \geq (1+\rho)\Lambda_1,$

(A3.3) $(r_1) : k_{11}(x_1^c)^{\theta_c}(S_1^k)^{\theta_k}(S_1^n)^{\theta_n}(e_1)^{\theta_e}(S_1^m)^{\theta_m} \geq c_1 + i_1,$

(A3.4) $(r_2) : k_{11}(x_2^c)^{\theta_c}(q^k(g, e^*, S^{m*})x_2^e)^{\theta_k}(q^n(g)x_2^e)^{\theta_n}(e_2)^{\theta_e}(S_2^m)^{\theta_m} \geq c_2 + i_2,$

(A3.5) $(z_1) : (1-\delta^k)S_0^k + k_5 i_1 \geq S_1^k,$

(A3.6) $(z_2) : (1-\delta^k)S_1^k + k_5 i_2 \geq q^k(g, e^*, S^{m*})x_2^e,$

(A3.7) $(\beta_1) : (1-\delta^n)S_0^n + k_2 x_1^n \geq S_1^n,$

(A3.8) $(\beta_2) : (1-\delta^n)S_1^n + k_2 x_2^n \geq q^n(g)x_2^e,$

(A3.9) $(\zeta_1) : k_4 x_0^e \geq x_1^e + x_1^n + x_1^l + x_1^c,$

(A3.10) $(\zeta_2) : k_4 x_1^e \geq x_2^e + x_2^n + x_2^l + x_2^c,$

for the year-2000 initial conditions $(x_0^e, S_0^k, S_0^n) = (\bar{x}_{2000}^e, \bar{S}_{2000}^k, \bar{S}_{2000}^n)$.

This is a concave program, and therefore the first-order conditions will be sufficient. We have 10 constraints and hence 10 Lagrangian multipliers, shown to the left of each constraint. There are 14 endogenous variables $(\Lambda_1, c_1, x_1^l, x_1^c, x_1^n, x_1^e, c_2, x_2^l, x_2^c, x_2^n, i_1, i_2, S_1^k, S_1^n)$ and hence 14 Kuhn-Tucker conditions, as follows.

$$KT1:(\partial\Lambda_1)\quad 1-\mu_1-(1+\rho)\mu_2=0;$$

$$KT2:(\partial c_1)\quad \mu_1\frac{\alpha_c\Lambda_1}{c_1}-r_1=0;$$

$$KT3:(\partial c_2)\quad \mu_2\frac{\alpha_c(1+\rho)\Lambda_1}{c_2}-r_2=0;$$

$$KT4:(\partial x_1^l)\quad \mu_1\frac{\alpha_l\Lambda_1}{x_1^l}-\zeta_1=0;$$

$$KT5:(\partial x_2^l)\quad \mu_2\frac{\alpha_l(1+\rho)\Lambda_1}{x_2^l}-\zeta_2=0;$$

$$KT6:(\partial S_1^k)\quad r_1\frac{\theta_k(c_1+i_1)}{S_1^k}-z_1+z_2(1-\delta^k)=0;$$

$$KT7:(\partial S_1^n)\quad \mu_1\frac{\alpha_n\Lambda_1}{S_1^n}+r_1\frac{\theta_n(c_1+i_1)}{S_1^n}-\beta_1+(1-\delta^n)\beta_2=0;$$

$$KT8:(\partial x_1^e)\quad -\zeta_1+\zeta_2k_4=0;$$

$$KT9:(\partial x_1^n)\quad \beta_1k_2-\zeta_1=0;$$

$$KT10:(\partial x_2^n)\quad \beta_2k_2-\zeta_2=0;$$

$$KT11:(\partial x_1^c)\quad r_1\frac{\theta_c(c_1+i_1)}{x_1^c}-\zeta_1=0;$$

$$KT12:(\partial x_2^c)\quad r_2\frac{\theta_c(c_2+i_2)}{x_2^c}-\zeta_2=0;$$

$$KT13:(\partial i_1)\quad -r_1+z_1k_5=0;$$

$$KT14:(\partial i_2)\quad -r_2+z_2k_5=0.$$

(a) From KT11, $\frac{\zeta_1}{r_1}=\theta_c\frac{c_1+i_1}{x_1^c}$. From KT4 and KT2, $\frac{\zeta_1}{r_1}=\frac{\mu_1\alpha_l\Lambda_1}{x_1^l}\frac{1}{\mu_1\alpha_c\Lambda_1}c_1=\frac{\alpha_lc_1}{\alpha_cx_1^l}$. It follows that

$$c_1=\frac{\theta_c\alpha_cx_1^l}{\alpha_lx_1^c-\theta_c\alpha_cx_1^l}i_1. \qquad \text{(a.1)}$$

Similarly, from KT12, $\frac{\zeta_2}{r_2} = \theta_c \frac{c_2 + i_2}{x_2^c}$. From KT5 and KT3,

$\frac{\zeta_2}{r_2} = \frac{\mu_2 \alpha_l (1+\rho)\Lambda_1}{x_2^l} \frac{1}{\mu_2 \alpha_c (1+\rho)\Lambda_1} c_2 = \frac{\alpha_l c_2}{\alpha_c x_2^l}$, yielding

$$c_2 = \frac{\theta_c \alpha_c x_2^l}{\alpha_l x_2^c - \theta_c x_2^l \alpha_c} i_2. \tag{a.2}$$

(b) From KT8

$$\frac{\zeta_2}{\zeta_1} = \frac{1}{k_4}, \tag{b.1}$$

whereas from KT9 and KT10,

$$\frac{\beta_2}{\beta_1} = \frac{\zeta_2}{\zeta_1}, \tag{b.2}$$

yielding

$$\frac{\beta_2}{\beta_1} = \frac{1}{k_4}. \tag{b.3}$$

From KT4 and KT9

$$\mu_1 \frac{\alpha_l \Lambda_1}{x_1^l} = \beta_1 k_2, \tag{b.4}$$

and from KT5 and KT10

$$\mu_2 \frac{\alpha_l (1+\rho)\Lambda_1}{x_2^l} = \beta_2 k_2. \tag{b.5}$$

Dividing (b.5) by (b.4)

$$\frac{\mu_2 x_1^l}{\mu_1 x_2^l}(1+\rho) = \frac{\beta_2}{\beta_1}, \tag{b.6}$$

which together with (b.3) yields

$$k_4 \mu_2 \frac{x_1^l}{x_2^l}(1+\rho) = \mu_1. \tag{b.7}$$

Substituting (b.7) into KT1 gives

$$1 = k_4 \mu_2 \frac{x_1^l}{x_2^l}(1+\rho) + (1+\rho)\mu_2,$$

i. e., $$\mu_2(1+\rho)\left[k_4\frac{x_1^l}{x_2^l}+1\right]=1,$$

or: $$\mu_2=\frac{x_2^l}{(1+\rho)(k_4x_1^l+x_2^l)}, \tag{b.8}$$

which together with (b.7) yields

$$\mu_1=\frac{k_4x_1^l}{k_4x_1^l+x_2^l}. \tag{b.9}$$

From (b.4) and (b.9),

$$\beta_1=\frac{\mu_1}{k_2}\frac{\alpha_l\Lambda_1}{x_1^l}=\frac{k_4\alpha_l x_1^l\Lambda_1}{k_2(k_4x_1^l+x_2^l)x_1^l},$$

i. e., $$\beta_1=\frac{k_4\alpha_l\Lambda_1}{k_2(k_4x_1^l+x_2^l)}, \tag{b.10}$$

and from (b.5) and (b.8),

$$\beta_2=\frac{\mu_2}{k_2}\frac{\alpha_l(1+\rho)\Lambda_1}{x_2^l}=\frac{\alpha_l x_2^l(1+\rho)\Lambda_1}{k_2(k_4x_1^l+x_2^l)(1+\rho)x_2^l},$$

i. e., $$\beta_2=\frac{\alpha_l\Lambda_1}{k_2(k_4x_1^l+x_2^l)}. \tag{b.11}$$

From KT9, $\zeta_1 = \beta_1 k_2$, i. e., using (b.10),

$$\zeta_1=\frac{k_4\alpha_l\Lambda_1}{k_4x_1^l+x_2^l}, \tag{b.12}$$

and, similarly, from KT10 and (b.11).

$$\zeta_2=\frac{\alpha_l\Lambda_1}{k_4x_1^l+x_2^l}. \tag{b.13}$$

Finally, from KT2 and (b.9),

$$r_1=\frac{k_4\alpha_c x_1^l\Lambda_1}{(k_4x_1^l+x_2^l)c_1}, \tag{b.14}$$

and from KT3 and (b.8)

$$r_2=\frac{x_2^l}{(1+\rho)(k_4x_1^l+x_2^l)}\frac{\alpha_c(1+\rho)\Lambda_1}{c_2},$$

i.e., $$r_2=\frac{\alpha_c x_2^l\Lambda_1}{(k_4x_1^l+x_2^l)c_2}. \tag{b.15}$$

From KT13 and (b.14)

$$z_1 = \frac{r_1}{k_5} = \frac{k_4 \alpha_c x_1^l \Lambda_1}{k_5 (k_4 x_1^l + x_2^l) c_1}, \tag{b.16}$$

and from KT14 and (b.15)

$$z_2 = \frac{r_2}{k_5} = \frac{x_2^l \alpha_c \Lambda_1}{k_5 (k_4 x_1^l + x_2^l) c_2}. \tag{b.17}$$

(c) Inserting (b.14), (b.9), (b.10) and (b.11) into KT7:

$$\mu_1 \frac{\alpha_n \Lambda_1}{S_1^n} + r_1 \frac{\theta_n (c_1 + i_1)}{S_1^n} - \beta_1 + (1-\delta^n)\beta_2 = 0,$$

we obtain $\frac{k_4 x_1^l}{k_4 x_1^l + x_2^l} \frac{\alpha_n \Lambda_1}{S_1^n} + \frac{k_4 x_1^l \alpha_c \Lambda_1}{(k_4 x_1^l + x_2^l) c_1} \frac{\theta_n (c_1 + i_1)}{S_1^n} - \frac{k_4 \alpha_l \Lambda_1}{k_2 (k_4 x_1^l + x_2^l)} + (1-\delta^n) \frac{\alpha_l \Lambda_1}{k_2 (k_4 x_1^l + x_2^l)} = 0$,

i. e., $$\frac{k_4 \alpha_n x_1^l}{S_1^n} + \frac{k_4 \alpha_c x_1^l \theta_n (c_1 + i_1)}{c_1 S_1^n} - \frac{k_4 \alpha_l}{k_2} + (1-\delta^n) \frac{\alpha_l}{k_2} = 0. \tag{c.1}$$

Inserting (b.14), (b.16), and (b.17) into KT6:

$$r_1 \frac{\theta_k (c_1 + i_1)}{S_1^k} - z_1 + z_2 (1-\delta^k) = 0,$$

we obtain $\frac{k_4 x_1^l \alpha_c \Lambda_1}{(k_4 x_1^l + x_2^l) c_1} \frac{\theta_k (c_1 + i_1)}{S_1^k} - \frac{k_4 x_1^l \alpha_c \Lambda_1}{k_5 (k_4 x_1^l + x_2^l) c_1} + \frac{x_2^l \alpha_c \Lambda_1}{k_5 (k_4 x_1^l + x_2^l) c_2} (1-\delta^k) = 0$,

i. e., $$\frac{k_4 x_1^l \theta_k (c_1 + i_1)}{c_1 S_1^k} - \frac{k_4 x_1^l}{k_5 c_1} + \frac{x_2^l (1-\delta^k)}{k_5 c_2} = 0. \tag{c.2}$$

(d) In summary, the Kuhn-Tucker conditions yield the following four equations involving only primal variables, which added to the 10 constraints, written as equalities, constitute a system of 14 equations in the 14 primal variables. The four equations are:

$$c_1 = \frac{\theta_c \alpha_c x_1^l}{\alpha_l x_1^c - \theta_c \alpha_c x_1^l} i_1, \tag{a.1}$$

$$c_2 = \frac{\theta_c \alpha_c x_2^l}{\alpha_l x_2^c - \theta_c \alpha_c x_2^l} i_2, \tag{a.2}$$

$$\frac{k_4 \alpha_n x_1^l}{S_1^n} + \frac{k_4 \alpha_c x_1^l \theta_n (c_1 + i_1)}{c_1 S_1^n} - \frac{k_4 \alpha_l}{k_2} + (1-\delta^n) \frac{\alpha_l}{k_2} = 0, \tag{c.1}$$

and $$\frac{k_4 x_1^l \theta_k (c_1 + i_1)}{c_1 S_1^k} - \frac{k_4 x_1^l}{k_5 c_1} + \frac{x_2^l (1-\delta^k)}{k_5 c_2} = 0\,. \tag{c.2}$$

(e) From (A3.5), $i_1 = \dfrac{S_1^k - (1-\delta^k) S_0^k}{k_5}$, (e.1)

which substituted into (a.1) yields $c_1 = \dfrac{\theta_c \alpha_c x_1^\ell}{\alpha_\ell x_1^c - \theta_c \alpha_c x_1^\ell} \dfrac{S_1^k - (1-\delta^k) S_0^k}{k_5}$ (e.2)

and $c_1 + i_1 = \left[\dfrac{\theta_c \alpha_c x_1^\ell}{\alpha_\ell x_1^c - \theta_c \alpha_c x_1^\ell} + 1 \right] \dfrac{S_1^k - (1-\delta^k) S_0^k}{k_5}$, i. e.,

$$c_1 + i_1 = \alpha_\ell x_1^c \frac{S_1^k - (1-\delta^k) S_0^k}{k_5(\alpha_\ell x_1^c - \theta_c \alpha_c x_1^\ell)}\,, \tag{e.3}$$

which in turn gives

$$\frac{c_1 + i_1}{c_1} = \frac{\alpha_l x_1^c}{\theta_c \alpha_c x_1^l}\,. \tag{e.4}$$

Similarly, from (A3.6), $i_2 = \dfrac{q^k x_2^e - (1-\delta^k) S_1^k}{k_5}$, (e.5)

which substituted into (a.2) yields $c_2 = \dfrac{\theta_c \alpha_c x_2^l}{\alpha_l x_2^c - \theta_c \alpha_c x_2^l} \dfrac{q^k x_2^e - (1-\delta^k) S_1^k}{k_5}$ (e.6)

and $$c_2 + i_2 = \alpha_l x_2^c \frac{q^k x_2^e - (1-\delta^k) S_1^k}{k_5(\alpha_l x_2^c - \theta_c \alpha_c x_2^l)}\,, \tag{e.7}$$

which in turn gives

$$\frac{c_2 + i_2}{c_2} = \frac{\alpha_l x_2^c}{\theta_c \alpha_c x_2^l}\,. \tag{e.8}$$

From (A3.7)

$$x_1^n = \frac{S_1^n - (1-\delta^n) S_0^n}{k_5}\,, \tag{e.9}$$

and from (A3.8)

$$x_2^n = \frac{q^n x_2^e - (1-\delta^n) S_1^n}{k_2}\,. \tag{e.10}$$

(f) Inserting (e.3) into (A3.3) we obtain

$$k_{11}(x_1^c)^{\theta_c}(S_1^k)^{\theta_k}(S_1^n)^{\theta_n}(e_1)^{\theta_e}(S_1^m)^{\theta_m} - \alpha_l x_1^c \frac{S_1^k - (1-\delta^k)S_0^k}{k_5(\alpha_l x_1^c - \theta_c \alpha_c x_1^l)} = 0, \qquad \text{(f.1)}$$

an equation of the form $\varphi_1(x_1^c, x_1^l, S_1^k, S_1^n) = 0$, while inserting (e.7) into (A3.4) yields

$$k_{11}(x_2^c)^{\theta_c}(q^k x_2^e)^{\theta_k}(q^n x_2^e)^{\theta_n}(e_2)^{\theta_e}(S_2^m)^{\theta_m} - \alpha_l x_2^c \frac{q^k x_2^e - (1-\delta^k)S_1^k}{k_5(\alpha_l x_2^c - \theta_c \alpha_c x_2^l)} = 0, \qquad \text{(f.2)}$$

an equation of the form $\varphi_2(x_2^c, x_2^l, S_1^k) = 0.$

Inserting (e.4) into (c.1), we obtain

$$\frac{k_4 x_1^l \alpha_n}{S_1^n} + \frac{k_4 x_1^l \alpha_c \theta_n}{S_1^n}\frac{\alpha_l x_1^c}{\theta_c \alpha_c x_1^l} - \frac{k_4 \alpha_l}{k_2} + (1-\delta^n)\frac{\alpha_l}{k_2} = 0,$$

or: $$\theta_c k_2 k_4 \alpha_n x_1^l + \theta_c k_2 k_4 \theta_n \alpha_l x_1^c - \theta_c \alpha_l [k_4 + 1 - \delta^n] S_1^n = 0, \qquad \text{(f.3)}$$

a linear equation of the form $\varphi_3(x_1^c, x_1^l, S_1^n) = 0.$

Inserting (e.4), (e.2) and (e.6) into (c.2) yields

$$\frac{k_4 x_1^l \theta_k}{S_1^k}\frac{\alpha_l x_1^c}{\theta_c \alpha_c x_1^l} - \frac{k_4 x_1^l}{k_5 \dfrac{\theta_c \alpha_c x_1^l}{\alpha_l x_1^c - \theta_c \alpha_c x_1^l}\dfrac{S_1^k - (1-\delta^k)S_0^k}{k_5}} + \frac{x_2^l(1-\delta^k)}{k_5 \dfrac{\theta_c \alpha_c x_2^l}{\alpha_l x_2^c - \theta_c \alpha_c x_2^l}\dfrac{q^k x_2^e - (1-\delta^k)S_1^k}{k_5}} = 0,$$

i. e., $$\frac{k_4 \theta_k \alpha_l x_1^c}{S_1^k \theta_c \alpha_c} - \frac{k_4(\alpha_l x_1^c - \theta_c \alpha_c x_1^l)}{\theta_c \alpha_c (S_1^k - (1-\delta^k)S_0^k)} + \frac{(1-\delta^k)(\alpha_l x_2^c - \theta_c \alpha_c x_2^l)}{\theta_c \alpha_c (q^k x_2^e - (1-\delta^k)S_1^k)} = 0, \qquad \text{(f.4)}$$

an equation of the form $\varphi_4(x_1^c, x_1^l, x_2^c, x_2^l, S_1^k) = 0.$

Inserting (e.9) into (A3.9), we obtain

$$x_1^e + \frac{S_1^n - (1-\delta^n)S_0^n}{k_2} + x_1^l + x_1^c - k_4 x_0^e = 0 \quad , \qquad \text{(f.5)}$$

a linear equation of the form $\varphi_5(x_1^c, x_1^l, x_1^e, S_1^n) = 0$, whereas the insertion of (e.10) into (A3.10) yields

$$x_2^e + \frac{q^n x_2^e - (1-\delta^n)S_1^n}{k_2} + x_2^l + x_2^c - k_4 x_1^e = 0 \quad , \qquad \text{(f.6)}$$

a linear equation of the form $\varphi_6(x_2^c, x_2^l, x_1^e, S_1^n) = 0$.

Finally, from (A3.1) and (A3.2), we have

$$(c_2)^{\alpha_c}(x_2^l)^{\alpha_l}(q^n x_2^e)^{\alpha_n}(\hat{S}^m - S_2^m)^{\alpha_m} = (1+\rho)(c_1)^{\alpha_c}(x_1^l)^{\alpha_l}(S_1^n)^{\alpha_n}(\hat{S}^m - S_1^m)^{\alpha_m}.$$

Inserting (e.6) and (e.2) into this equation yields

$$\left(\frac{x_2^l[q^k x_2^e-(1-\delta^k)S_1^k]}{\alpha_l x_2^c-\theta_c\alpha_c x_2^l}\right)^{\alpha_c}(x_2^l)^{\alpha_l}(q^n x_2^e)^{\alpha_n}(\hat{S}^m-S_2^m)^{\alpha_m}$$
$$=(1+\rho)\left(\frac{x_1^l\left[S_1^k-(1-\delta^k)S_0^k\right]}{\alpha_l x_1^c-\theta_c\alpha_c x_1^l}\right)^{\alpha_c}(x_1^l)^{\alpha_l}(S_1^n)^{\alpha_n}(\hat{S}^m-S_1^m)^{\alpha_m}, \quad \text{(f.7)}$$

an equation of the form $\varphi_7(x_1^c, x_1^l, x_2^c, x_2^l, S_1^k, S_1^n)=0$.

The seven equations (f.1) to (f.7) form a system in the seven unknowns $(x_1^c, x_1^l, x_1^e, x_2^c, x_2^l, S_1^k, S_1^n)$. We numerically solve these seven equations using *Mathematica,* and then compute all the other values (including Λ_1, which can be obtained from (A3.1)). We check that all values and Lagrangian multipliers are non-negative to be assured that we have found a solution.

APPENDIX 4. CALIBRATIONS

For calibration purposes, we interpret that generations live for 25 years. In this appendix flow variables are typically defined as per year average, and it is understood that stocks are located in the last year of life of a generation.

A4.1. Variables

S_t^k = capital stock available to Generation *t* (in thousands of dollars per capita).

S_t^n = stock of knowledge available to Generation *t* (in thousands of dollars per capita).

S_t^m = CO_2 concentration in the atmosphere above the equilibrium pre-industrial level at the end of Generation *t*'s life (in GtC).

x_t = average annual efficiency units of time (labor and leisure) available to Generation *t* (in efficiency units per capita).

x_t^e = average annual labor devoted to education by Generation *t* (in efficiency units per capita).

x_t^c = average annual labor devoted to the production of output by Generation *t* (efficiency units per capita).

x_t^l = annual average leisure by Generation *t* (in efficiency units per capita).

x_t^n = average annual labor devoted to the production of knowledge by Generation t (in efficiency units per capita).

c_t = annual average consumption by Generation t (in thousands of dollars per capita).

i_t = average annual investment by Generation t (in thousands of dollars per capita).

e_t = average annual emissions of CO_2 from fuel and cement in GtC by Generation t (in GtC).

A4.2. Parameters

α_j = exponents of the quality of life function for $j \in \{c$ (consumption), l (leisure), n (stock of knowledge), and m (quality of the biosphere)$\}$.

k_{11} = parameter of the production function f.

k_2 = parameter of the law of motion of the stock of knowledge.

k_4 = parameter of the education production function.

k_5 = parameter of the law of motion of capital.

θ_j = exponents of the inputs in the production function f for $j \in \{c$ (labor), k (stock of capital), n (stock of knowledge), e (emissions of CO_2), m (atmospheric carbon concentration)$\}$.

δ^k = depreciation rate of the stock of capital (per generation).

δ^n = depreciation rate of the stock of knowledge (per generation).

$\hat{S}^m$ = catastrophic level of carbon concentration in the atmosphere above the equilibrium pre-industrial level (in GtC).

ρ = generational rate of growth of the QuoL.

$\hat{\rho}$ = annual rate of growth of the QuoL ($\rho = (1+\hat{\rho})^{25}$).

A4.3. Functions

Quality-of-life function (QuoL): $\tilde{\Lambda}(c_t, x_t^l, S_t^m, S_t^n) \equiv (c_t)^{\alpha_c}(x_t^l)^{\alpha_l}(\hat{S}^m - S_t^m)^{\alpha_m}(S_t^n)^{\alpha_n}$.

Production function f (Model E):

$$f(x_t^c, S_t^k, S_t^n, e_t, S_t^m) \equiv k_{11}(x_t^c)^{\theta_c}(S_t^k)^{\theta_k}(S_t^n)^{\theta_n}(e_t)^{\theta_e}(S_t^m)^{\theta_m}, \theta_c + \theta_c + \theta_n = 1.$$

Law of motion of physical capital: $S_t^k \leq (1-\delta^k)S_{t-1}^k + k_5\, i_t$.

Law of motion of the stock of knowledge: $S_t^n \leq (1-\delta^n)S_{t-1}^n + k_2\, x_t^n$.

Education production function: $x_t \leq k_4 x_{t-1}^e$.

A4.4. The calibration of the Quality-of-Life (QuoL) function

We take the exponent of leisure to be twice that of consumption ($\alpha_l = 2\,\alpha_c$) and calibrate $\alpha_n/\alpha_c = 0.05$ as the average ratio of expenditure in knowledge over expenditure in consumption during the period 1953-2000.[18]

Next, we calibrate the ratio α_m/α_c by the Stern Review statement that a 5ºC increase in the global temperature over the pre-industrial level would imply a health related damage equivalent to a 5% loss of global GDP (page x).[19] We can read the statement of the Stern Review as saying that a 5% decrease in consumption is equivalent to suffering an atmospheric CO_2 concentration of $\tilde{S}^m$, yielding

$$(.95c)^{\alpha_c}(x^{\ell})^{\alpha_\ell}(S^n)^{\alpha_n}(\hat{S}^m - S^m)^{\alpha_m} = (c)^{\alpha_c}(x^{\ell})^{\alpha_\ell}(S^n)^{\alpha_n}(\hat{S}^m - \tilde{S}^m)^{\alpha_m},$$

that is,

$$(.95)^{\alpha_c}(\hat{S}^m - S^m)^{\alpha_m} = (\hat{S}^m - \tilde{S}^m)^{\alpha_m}.$$

Taking logs,

$$\alpha_c \ln(0.95) = \alpha_m\left(\ln\left(\hat{S}^m - \tilde{S}^m\right) - \ln\left(\hat{S}^m - S^m\right)\right).$$

We take a 5ºC increase in temperature to be associated with CO_2 equivalent (CO_2e) concentrations of 1470 GtC (Stern 2007, Figure 2 in page v). Because we only consider CO_2 emissions (which account for 84% of all GHG) and we compute values above pre-industrial level (595.5 GtC), we adopt the value $\tilde{S}^m = \frac{1470}{1.16} - 595.5 = 671.74$ GtC.

We consider that an increase in temperature of 6º-8ºC (relative to pre-industrial level) would have catastrophic impacts.[20] We take this temperature increases to be associated with CO_2 equivalent concentrations of 750 ppm (or 1597 GtC), the lower bound of the studies reported in the Stern

[18] R&D data are given by the NSF. Data on investment in computer components and software is taken from BEA. Data on software in the public sector are constructed taking the value of public investment in equipment and software and assuming that the share of software in expenditure is the same in the public and private sectors.

[19] This is also in line with Nordhaus and Boyer (2000) who estimate a total cost (market and non-market) of between 9 to 11% of global GDP for a 6ºC warming (as quoted in Stern, 2007, p.148).

[20] The Stern Review consistently associates catastrophic consequences to temperature increases of 6-8ºC, like, for example, sea level rise threatening major world cities (including London, Shanghai, New York, Tokyo and Hong Kong), entire regions experiencing major declines in crop yields and high risk of abrupt, large scale shifts in the climate system (Figure 2 in page v), and catastrophic major disruptions and large-scale movements of population (Table 3.1 in p.57).

Review (2007, p.12). As before, adjusting for all gases and subtracting pre-industrial levels, we obtain $\hat{S}^m = \frac{1575}{1.16} - 590 = 781.2$.

It follows that

$$\frac{\alpha_m}{\alpha_c} = \frac{\ln 0.95}{\ln(781.2 - 671.74) - \ln(781.2 - 177.1)} = 0.03.$$ [21]

Finally, we normalize $\alpha_c + \alpha_l + \alpha_m + \alpha_n = 1$, and obtain the values reported in Table A1.

A4.5. The calibration of the production function

We construct time series for the stocks of capital, knowledge, and human capital. (See details below.) We take the labor income share equal to two thirds, and compute the average share of physical capital and knowledge in the total stock of capital for the period 1960-2000, corresponding to 5/6 and 1/6, respectively. We calibrate the production function of Section 4.1 with these data.

Model E uses the production function

$$f(x_t^c, S_t^k, S_t^n, S_t^m, e_t) \equiv k_{11}(x_t^c)^{\theta_c}(S_t^k)^{\theta_k}(S_t^n)^{\theta_n}(S_t^m)^{\theta_m}(e_t)^{\theta_e},$$

with the following inputs: first the more usual labor, physical capital and knowledge, to which we add the environmental stock and emissions. We assume constant returns to scale in the first three inputs, i. e., $\theta_c + \theta_k + \theta_n = 1$. Hence, $\theta_c = 2/3$, $\theta_k = 5/18$ and $\theta_n = 1/18$, representing the income share of each input.

We calibrate $\theta_e = 0.091$ as the "elasticity of output with respect to carbon services" from RICE99 in Nordhaus and Boyer (2000). For the calibration of θ_m, the elasticity of output to the CO_2 concentration in the atmosphere, we assume that doubling the CO_2 concentration from pre-industrial levels would increase temperature by 2.5ºC (Stern, 2007, p.7), [22] and that a 2.5ºC increase in temperature is associated with a 1.5% loss of total GDP (Nordhaus and Boyer, 2000, p.91). Hence,

$$\theta_m = \frac{\%\Delta y}{\%\Delta S^m} = \frac{\%\Delta y}{\%\Delta T}\frac{\%\Delta T}{\%\Delta S^m} = -\frac{.015}{2} = -.0075,$$

where y is GDP per capita and T is global temperature.

[21] As a reference, the US currently devotes approximately 2% of its gross domestic product to all forms of environmental protection.

[22] The Stern Review asserts that temperature would increase 1.5º-4.5ºC (if we consider feedback effects) and 1ºC as direct effects.

Finally, we calibrate k_{11} to year-2000 values:[23]

$$k_{11} = \frac{y_{2000}\left(S^m_{2000}\right)^{-\theta_m}}{e^{\theta_e}_{2000}\left(x^c_{2000}\right)^{\theta_c}\left(S^k_{2000}\right)^{\theta_k}\left(S^n_{2000}\right)^{\theta_n}} = \frac{34.78\cdot 177.1^{.0075}}{6.56^{.091}\,0.3956^{2/3}73.65^{5/18}15.64^{1/18}} = 14.688.$$

The time series of the stocks of capital and knowledge are constructed by the perpetual inventory method, using US data for 1960-2000 and taking 1960 as initial value. For physical capital, $S^k_{1960} = \frac{i^k_{1960}}{\hat{\delta}^k + g^k} = \frac{2.51}{0.06+0.038} = 25.63$ thousands of constant 2000 dollars per capita, where i^k represents total (private and public) investment per capita minus expenditure in software, and the values for $\hat{\delta}^k$ (the annual rate of depreciation, set at 0.06) and g^k (the average yearly growth rate of investment between 1960-1970, set at 0.038), are justified in A4.6 below. Similarly, for the initial stock of knowledge, $S^n_{1960} = \frac{i^n_{1960}}{\hat{\delta}^n + g^n} = \frac{0.421}{0.06+0.041} = 4.21$ thousands of constant 2000 dollars per capita, where i^n represents total expenditure per capita in R&D plus public and private investment in software[24], and the values for $\hat{\delta}^n$ (the rate of depreciation) and g^n (the average yearly growth rate between 1960-1970) are justified in A4.7 below.

A4.6. The calibration of the law of motion of the stock of physical capital

Physical capital investment is equal to private plus public investment less investment in software. We take $\hat{\delta}^k = 0.06$ as the annual rate of depreciation (Thomas Cooley and Edward Prescott, 1995). In generational terms, $\delta^k = 0.787$.

To approximate the year-to-year discounting, we take i = average investment in physical capital of Generation t per year, and compute that, at the end of Generation t's life, the accumulated

[23] Table A2 reports the values of the stocks and flows for the year 2000.
[24] Data on R&D is derived from Research and Development in Industry, Academic Research and Development Expenditures, Federal Funds for Research and Development, and the Survey of Research and Development Funding and Performance by Nonprofit Organizations (National Science Foundation, 2003). Data on public investment in software are constructed taking the value of public investment in equipment and software (U.S. Bureau of Economic Analysis 2007) and assuming the same share of software in private and public investment.

investment amounts are i + i×(1-$\hat{\delta}^k$) + i×(1-$\hat{\delta}^k$)^2 + …+ i×(1-$\hat{\delta}^k$)^{24} = $\frac{1-(1-\hat{\delta}^k)^{25}}{1-(1-\hat{\delta}^k)} i$. Thus, since 1-$\hat{\delta}^k$ = 0.94, the parameter $k_5 = \frac{1-(1-\hat{\delta}^k)^{25}}{1-(1-\hat{\delta}^k)}$ = 13.1182.

A4.7. The calibration the law of motion of the stock of knowledge

The yearly depreciation rate for knowledge commonly used is much lower than the one for capital (e.g. the Bank of Spain uses $\hat{\delta}^n = 0.15$, which would mean that knowledge dissipates almost entirely in one generation). We believe that the discount factor should be higher because of the intergenerational-public-good character of knowledge. A dollar invested in R&D by a firm may well generate no returns to the firm 25 years later, yet its impact to the accumulation of social knowledge capital may be substantial. Thus, as an approximation we take the depreciation rate of the stock of knowledge to be the same as that of physical capital, i.e., in generational terms, $\delta^n = \delta^k = 0.787$.

We approximate the year-to-year discounting with the same argument as in physical capital. If we denote by i^n the average annual expenditure per capita in knowledge, then we could write $(1-\delta^n)S_{t-1}^n + \frac{1-(1-\delta^n)^{25}}{1-(1-\delta^n)} i^n > S_t^n$. But, because investment in knowledge is written in efficiency units of labor per capita, then $\frac{1-(1-\delta^n)^{25}}{1-(1-\delta^n)} i_t^n = k_2 x_t^n$, that is, $k_2 = \frac{1-(1-\delta^n)^{25}}{1-(1-\delta^n)} \frac{i_t^n}{x_t^n}$, where $\frac{i_t^n}{x_t^n}$ is the wage of an efficiency unit of labor.

Now, we estimate $\frac{i_t^n}{x_t^n} = \frac{i_t^n}{\epsilon^n (1/3) x_t}$ where (1/3) x_t is the total efficient units of labor and ϵ^n the share of labor devoted to the production of knowledge. We take ϵ^n = 0.05 (5% of total labor) and use the average values for the last generation (1976-2000) to obtain $\frac{i_t^n}{x_t^n} = \frac{i_{76-00}^n}{0.05(1/3)x_{76-2000}} = \frac{0.99}{0.02} =$ 45.59 thousands of 2000 dollars.

Hence, $k_2 = \frac{1-(1-\hat{\delta}^n)^{25}}{1-(1-\hat{\delta}^n)} \frac{i^n}{x^n}$ = 13.1182×45.59 = 598.06.

A4.8. The calibration of the education production function

Write $k_4 = \frac{x_t}{x_{t-1}^e}$. Both the numerator and the denominator are in efficiency units. We take the average yearly growth rate of human capital stock equal to $\hat{s}$ = 0.067% (de la Fuente and Domenech 2001). Then, the growth factor of human capital per generation is (1 + s) = (1 + $\hat{s}$)[25] = 1.0067[25], and we can write, for some T, $k_4 = \frac{(1+s)^T \hat{x}_t}{(1+s)^{T-1}\hat{x}_{t-1}^e} = (1+s)\frac{\hat{x}_t}{\hat{x}_{t-1}^e}$, where once more the "hats" represent annual data. Assuming the ratios to remain constant over time, taking education to involve 10% of labor, and labor to account for 1/3 of total time, we get $\frac{\hat{x}_t}{\hat{x}_{t-1}^e} = \frac{\hat{x}_t}{\hat{x}_t^e} = \frac{\hat{x}_t}{0.1 \cdot \frac{1}{3}\hat{x}_t} = 30$.

Hence $k_4 = (1.0067)^{25} \cdot 30 = 35.451$.

A4.9. Initial values in the benchmark year 2000

The values for the stock of physical capital, $\overline{S}_{2000}^k$ = 73.65, and knowledge, $\overline{S}_{2000}^n$ = 15.64 (in thousands of 2000 dollars per capita), are obtained by using the perpetual inventory method as reported in A4.6 and A4.7.

We take $\overline{S}_{2000}^m$ = 177.1 GtC (or 83 ppm) as the year 2000 atmospheric CO_2 concentration above pre-industrial level (of approximately 590GtC in 1850) from the CAIT Indicator Framework Paper (World Resource Institute (WRI) 2005, page 13). As for emissions, we take $\overline{e}_{2000}$ = 6.56 GtC also from the World Resource Institute (2005) as the world annual CO_2 emissions from energy (fossil fuels and cement) in GtC.[25]

The series of human capital stock (in efficiency units) is constructed normalizing year 1950 equal to 1 and taking the average yearly growth rate of human capital stock equal to 0.67% (de la Fuente and Domènech, 2001). Hence, $x_t = 1.0067^{t-1950}$ in 1950-efficiency units, and therefore $\overline{x}_{2000}$ = 1.0067^{50} = 1.396.

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[25] Once we include CO_2 emissions from land use change (7.62 $GtCO_2$) and from other Kyoto gases (9.72 $GtCO_2e$), our value (41.36 $GtCO_2e$) is consistent with the 42 GtCO2e total GHG emissions in 2000 reported in the Stern Review (page 170).

We take education to occupy 10% of labor time. And consequently, $\overline{x}^{e}_{2000}$ = 1.396×1/3×0.1 = 0.0465 in 1950-efficiency units.

Finally, for total income, consumption and investment see the calibration of the production functions in A4.5.

Table A4.1. Calibrated parameter values

Parameter	Value
α_c	0.325
α_l	0.650
α_n	0.016
α_m	0.009
k_{11}	14.688
k_2	598.060
k_4	35.451
k_5	13.118
k_6	0.297
θ_c	0.6667
θ_k	0.2778
θ_n	0.0555
θ_m	-0.0075
θ_e	0.0910
δ^k	0.787
δ^n	0.787
$\hat{S}^m$	781.2

Table A4.2. Initial values in the benchmark year (2000)

Stocks	Value	Units
$\overline{S}^{k}_{2000}$	73.65	thousands of 2000 dollars per capita.
$\overline{S}^{n}_{2000}$	15.64	thousands of 2000 dollars per capita.
$\overline{S}^{m}_{2000}$	177.1	GtC above pre-industrial level.
$\overline{x}_{2000}$	1.396	1950-efficiency units per capita.

Flows	Value	Units
$\overline{x}^{e}_{2000}$	0.0465	1950-efficiency units per capita.
$\overline{c}_{2000}$	23.88	thousands of 2000 dollars per capita.
$\overline{i}_{2000}$	7.59	thousands of 2000 dollars per capita.
$\overline{e}_{2000}$	6.56	GtC.
$\overline{y}_{2000}$	34.78	thousands of 2000 dollars per capita.

APPENDIX 5. COMPUTED PATHS FOR SECTION 4

As noted in the main text, we choose the emissions and concentration values $\left\{e_1, S_1^m\right\} = \{6.97, 303\}$ $\left\{e_2, S_2^m\right\} = \{4.43, 354\}$, $\left\{e_t, S_t^m\right\} = \left\{e^*, S^{m*}\right\} = \{0.4, 363\}, t \geq 3$, and solve the model for all economic variables and the resulting quality of life. We separately consider three sustained growth rates for the quality of life, namely $\hat{\rho} = 0.00$, $\hat{\rho} = 0.01$ and $\hat{\rho} = 0.02$, where $\hat{\rho}$ is the rate of growth of the QuoL *per annum*, with corresponding rates of growth per generation equal to $\rho = 0.00$, $\rho = 0.28$ and $\rho = 0.64$, respectively.

Table A5.1: $\hat{\rho} = 0.00$ (no growth)

Gen	$\Lambda_t / \Lambda_{t_0}$	$\Lambda_t / \Lambda_{t-1}$	c_t	c_t / c_{t-1}	x_t^e	x_t^c	x_t^n	x_t^l	i_t	S_t^k	S_t^n
2000	1.	1.	23.88	-	0.04653	0.3955	0.0233	0.9307	7.59	73.65	15.64
1	1.3110	1.3110	40.399	1.6917	0.04660	0.4779	0.0608	1.0643	14.02	199.62	39.72
2	1.3110	1.	37.931	0.9390	0.05138	0.4444	0.0586	1.0977	8.14	149.26	43.48
3	1.3111	1.0000	31.759	0.8373	0.05138	0.5129	0.0572	1.2000	8.95	149.26	43.48
4	1.3111	1	31.759	1	0.05138	0.5129	0.0572	1.2000	8.95	149.26	43.48

Gen	x_t^e (%)	x_t^c (%)	x_t^n (%)	x_t^l (%)	x_t
2000	0.0333	0.2833	0.0167	0.6667	1.396
1	0.0282	0.2897	0.0369	0.6452	1.650
2	0.0311	0.2690	0.0355	0.6645	1.652
3	0.0282	0.2815	0.0314	0.6588	1.821
4	0.0282	0.2815	0.0314	0.6588	1.821

Table A5.2: $\hat{\rho} = 0.01$ (1% annual growth or 28% generational growth)

Gen	$\Lambda_t / \Lambda_{t_0}$	$\Lambda_t / \Lambda_{t-1}$	c_t	c_t / c_{t-1}	x_t^e	x_t^c	x_t^n	x_t^l	i_t	S_t^k	S_t^n
2000	1.	1.	23.88	-	0.04653	0.3955	0.0233	0.9307	7.59	73.65	15.64
1	1.2999	1.2999	40.056	1.6774	0.06043	0.4737	0.0603	1.0552	13.89	197.88	39.38
2	1.6671	1.2824	48.281	1.2054	0.08548	0.5779	0.0796	1.3994	11.53	193.38	55.98
3	2.1380	1.2824	51.993	1.0769	0.10987	0.8544	0.1004	1.9656	15.81	248.56	71.95
4	2.7418	1.2824	66.829	1.2853	0.14122	1.0982	0.1290	2.5265	20.32	319.48	92.48

Gen	x_t^e (%)	x_t^c (%)	x_t^n (%)	x_t^l (%)	x_t
2000	0.0333	0.2833	0.01667	0.6667	1.396
1	0.0366	0.2872	0.03654	0.6397	1.649
2	0.0399	0.2697	0.03715	0.6532	2.142
3	0.0363	0.2819	0.03313	0.6486	3.030
4	0.0363	0.2819	0.03313	0.6486	3.895

Table A5.3: $\hat{\rho} = 0.02$ (2% annual growth or 64% generational growth)

Gen	$\Lambda_t / \Lambda_{t_0}$	$\Lambda_t / \Lambda_{t-1}$	c_t	c_t / c_{t-1}	x_t^e	x_t^c	x_t^n	x_t^l	i_t	S_t^k	S_t^n
2000	1.	1.	23.88	-	0.0465	0.3955	0.0233	0.9307	7.59	73.65	15.64
1	1.2859	1.2859	39.618	1.6591	0.0780	0.4684	0.0595	1.0437	13.72	195.65	38.94
2	2.1097	1.6406	61.176	1.5441	0.1413	0.7441	0.1058	1.7750	15.76	248.44	71.56
3	3.4612	1.6406	84.505	1.3813	0.2328	1.4080	0.1717	3.1961	27.18	409.43	117.90
4	5.6784	1.6406	139.260	1.6480	0.3837	2.3204	0.2830	5.2671	44.79	674.74	194.40

Gen	x_t^e (%)	x_t^c (%)	x_t^n (%)	x_t^l (%)	x_t
2000	0.0333	0.2833	0.0166	0.6667	1.396
1	0.0473	0.2839	0.0361	0.6327	1.650
2	0.0511	0.2690	0.0382	0.6417	2.766
3	0.0465	0.2811	0.0343	0.6381	5.009
4	0.0465	0.2811	0.0343	0.6381	8.254

APPENDIX 6. NORDHAUS'S SOCIAL WELFARE FUNCTION AND THE CALIBRATION OF ITS PARAMETERS

A6.1. A long-lived consumer

The traditional theory of economic growth considers the accumulation of physical capital, in particular the tradeoff between present consumption and the enhanced consumption possibilities of future generations offered by saving. It often postulates a long-lived representative consumer, whose preferences are representable in an additively separable manner as the discounted sum of future single-date subutilities, one for each future date. If only the consumption c_t at each date enters the single-date subutility function, and if such function is of the form $\frac{1}{1-\eta}c^{1-\eta}$, then the consumer's preferences are represented by the utility function

$$\sum_{t=1}^{T}\frac{1}{1-\eta}c^{1-\eta}\frac{1}{(1+\delta)^t} \; , \qquad \text{(A6.1)}$$

where $T \leq \infty$, $\eta > 0$ (for $\eta = 1$, $\ln c$ replaces $\frac{1}{1-\eta}c^{1-\eta}$), and where the discount factor $\frac{1}{1+\delta}$ (or the discount rate δ) reflects the consumer's marginal rate of intertemporal substitution: a more impatient consumer has a larger δ, and attaches little value to a unit of consumption made available to him far into the future.

A6.2. Nordhaus's social welfare function

The social welfare function in Nordhaus (1991, 1994, 2008), and Nordhaus and Boyer (2000), see (9) in Section 6.2 above, is similar to (A6.1), but with a quite different meaning. Now $t = 1, 2, \ldots$ represent generations, and c_t is the consumption per capita of Generation t. As noted in Section 6.2 above, Nordhaus's (2008a) calls δ and η "central" and "unobserved normative parameters," affecting "the relative importance of the different generations." The parameter δ is a "pure social time discount rate:" a high δ means that the welfare of a generation born far into the future counts very little in the social welfare function. The second one represents "the aversion to inequality of different generations." Informally speaking, if the rates of growth turn out to be negative, then δ and η push in opposite directions, a high δ favoring the earlier generations and a high η favoring the later, less well off, generations. But for positive rates of growth, when the latter generations are better off, high values of either δ or η favor the earlier generations. This is the case in the paths proposed by Nordhaus (2008a, b).

A6.3. The calibration of the parameters

Nordhaus (2008a,b) calibrates η and $\hat{\delta}$ as follows. First, he adopts the "Ramsey equation"

$$\hat{r} = \hat{\delta} + \eta \hat{g}, \qquad \text{(A6.2)}$$

where $\hat{r}$ is the real per year rate of interest on capital and $\hat{g}$ is the per year rate of growth of consumption. Nordhaus (2008, p. 60-61) justifies equation (A6.2) by the maximization of the function (A6.1) subject to some constraints. In his words, and noting that his symbol ρ (resp. α) corresponds to the δ (resp. η) of the present paper:

> "The basic economics can be described briefly. Assume a time discount rate of ρ and a consumption elasticity of α. Next, maximize the social welfare function described earlier and in the Appendix with a constant population and a constant rate of growth per generation g^*. This yields the standard equation for the equilibrium real return on capital, r^*, given by $r^* = \rho + \alpha g^*$."

Second, he infers $\hat{r}$ and $\hat{g}$ from "observed economic outcomes as reflected by interest rates and rates of return on capital" (p. 33-34).

Third, he chooses $\hat{\delta}$ and η subject to the Ramsey equation, which gives one degree of freedom. In particular, Nordhaus (2008, p. 178) takes the values $(\hat{r}, \hat{g}) = (0.055, 0.02)$. Equation (A6.2) then holds for any $(\hat{\delta}, \eta)$ pair satisfying $\hat{\delta} = 0.055 - 0.02\eta$, in particular by the values $(\hat{\delta}, \eta) =$ (0.015, 2) chosen by Nordhaus (2008a).[26]

Summarizing, equation (A6.2) is obtained by the constrained maximization of (A6.1), whereas $\hat{r}$ and $\hat{g}$ are deduced from observed behavior. Inserting $\hat{r}$ and $\hat{g}$ into (A6.2) could make sense if, as in Section A6.1 above, observed behavior was generated by a single long-lived consumer who solves the optimization program. But in this case the parameters $(\hat{\delta}, \eta)$ would be "positive," rather than "normative," whereas Nordhaus's analysis concerns a world of many distinct generations, with parameters $(\hat{\delta}, \eta)$ which are "normative." It is peculiar to think of rates of return observed in

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[26] Elsewhere in the book he refers to a $\hat{r}$ of 0.04 (pp. 9-11) and to a $\hat{g}$ of 0.013 (p. 108).

the market as depending on these "normative" parameters, in particular on the aversion, by past and current market participants, to inequality among generations.

In addition, because Nordhaus (2008a) gives little detail on the constraints of the optimization program leading to (A6.2), it is hard to evaluate the assumption that r^* and g^* are constant at the solution. In any event, the solution paths will depend on the initial conditions on the stocks, so that the constancy of rates can typically be justified only asymptotically.[27]

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[27] Consider, for instance, the traditional Ramsey problem, with capital but without environmental stocks: An infinitely lived consumer maximizes $\int_0^\infty \frac{1}{1-\eta} c(t)^{1-\eta} e^{-\delta t} dt$ subject to the law of motion of capital k_R and the initial condition $k_R(0) = k_0$. Let capital depreciate at the rate δ_R, and let the production function be $Ak_R{}^\psi e^{nt}$, where $\psi \in (0,1)$ and $n \geq 0$ is the rate of exogenous technological change. The constraint is then $\dot{k}_R(t) \leq Ak_R(t)^\psi e^{nt} - c(t) - \delta_R k_R(t)$. Writing the Hamiltonian as $H(c, k_R, \lambda) =$ $(1-\eta)^{-1} c^{1-\eta} e^{-\delta t} + \lambda[Ak_R{}^\psi e^{nt} - c - \delta_R k_R]$, at the solution path one must have (see, e. g., George Hadley and Murray Kemp, 1971, Th. 4.3.1) (a) $\frac{\partial H}{\partial c} = 0$, i. e., $c^{-\eta} e^{-\delta t} - \lambda = 0$, and (b) $-\frac{\partial H}{\partial k_R} = \dot{\lambda}$, i. e., $-\lambda(A\psi k_R{}^{\psi-1} e^{nt} - \delta_R) = \dot{\lambda}$. From (a), $-\eta c^{-\eta-1} \cdot \dot{c} \cdot e^{-\delta t} + c^{-\eta} \cdot e^{-\delta t}.(-\delta) = \dot{\lambda}$, which together with (b), using (a) again and dividing through by $c^{-\eta} \cdot e^{-\delta t}$, gives $A\psi k_R{}^{\psi-1} e^{nt} - \delta_R = \delta + \eta \cdot \frac{\dot{c}}{c}$, a time-dependent form of (A6.2). Assume now that $\frac{\dot{c}}{c} = \bar{g}$, a constant, i. e., $c(t) = c_0 e^{\bar{g}t}$ for some $c_0 > 0$. The last equation then reads $A\psi k_R(t)^{\psi-1} e^{nt} = \delta_R + \delta + \eta\bar{g}$, i. e., $k_R(t) = (\delta_R + \delta + \eta\bar{g})^{\frac{1}{\psi-1}} (A\psi)^{\frac{1}{1-\psi}} e^{\frac{n}{1-\psi}t}$, and the initial condition $k_R(0) = k_0$ requires $k_0 = (\delta_R + \delta + \eta\bar{g})^{\frac{1}{\psi-1}} (A\psi)^{\frac{1}{1-\psi}}$. Writing $k_R(t) = k_0 e^{\frac{n}{1-\psi}t}$ and dividing through by k_R, the law of motion becomes $\frac{n}{1-\psi} = Ak^{\psi-1} e^{nt} - \frac{c}{k} - \delta_R$, i. e., $\frac{n}{1-\psi} = A[k_0 e^{\frac{n}{1-\psi}t}]^{\psi-1} e^{nt} - \frac{c_0}{k_0} e^{\bar{g}t} e^{-\frac{n}{1-\psi}t} - \delta_R$, or $\frac{n}{1-\psi} = Ak_0{}^{\psi-1} - \frac{c_0}{k_0} e^{\bar{g}t} e^{-\frac{n}{1-\psi}t} - \delta_R$, $\forall t$, which implies that $\bar{g} = \frac{n}{1-\psi}$. But then the parameters $(\eta, \delta, A, \psi, n, \delta_R, k_0)$ must belong to the set of measure zero defined by the equality $k_0 = (\delta_R + \delta + \eta \frac{n}{1-\psi})^{\frac{1}{\psi-1}} (A\psi)^{\frac{1}{1-\psi}}$.

A6.4. Discounted utilitarianism

The parameter η could also be interpreted, following the classical utilitarians, as an index of the concavity of a common, cardinal and interpersonally unit-comparable utility function displaying decreasing marginal utility.[28] The function (9) would then be the social welfare function of discounted utilitarianism. But we find discounted utilitarianism ethically unacceptable, at least for the high (pure time) discount rates δ typically used in the literature, which put a weight on the utility of future generations much lower than that of the present generation. The only ethical justification for putting a lower weight on the welfare of future generations in the utilitarian calculus should be based on a positive probability of extinction of mankind. As argued in the Stern Review, this rationale would perhaps support a discount rate of $\hat{\delta} = 0.001 = 0.1\%$ *per annum*, associated with a 0.905 probability of mankind's surviving 100 years. Of course, a rigorous development of this idea requires an explicit model of uncertainty: see Section 5 above and Llavador *et al.* (2008), where the problem is formulated as one of an impartial observer with von Neumann-Morgenstern preferences over uncertain future worlds.

[28] See Roemer (1998) for definitions.

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