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"A dynamic analysis of human welfare in a warming planet"☆

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ABSTRACT

Climate science indicates that climate stabilization requires low GHG emissions. Is this consistent with nondecreasing human welfare?

Our welfare or utility index emphasizes education, knowledge, and the environment. We construct and calibrate a multigenerational model with intertemporal links provided by education, physical capital, knowledge and the environment.

We reject discounted utilitarianism and adopt, first, the *Pure Sustainability Optimization* (or Intergenerational Maximin) criterion, and, second, the *Sustainable Growth Optimization* criterion, that maximizes the utility of the first generation subject to a given future rate of growth. We apply these criteria to our calibrated model via a novel algorithm inspired by the turnpike property.

The computed paths yield levels of utility higher than the level at reference year 2000 for all generations. They require the doubling of the fraction of labor resources devoted to the creation of knowledge relative to the reference level, whereas the fractions of labor allocated to consumption and leisure are similar to the reference ones. On the other hand, higher growth rates require substantial increases in the fraction of labor devoted to education.

1. Introduction

Since the late 1980s, scientists have become increasingly concerned with the effect of the emission of greenhouse gases (GHGs) on global temperature. The Intergovernmental Panel on Climate Change (IPCC) has now issued four reports, documenting the conjecture, expressed with increasing levels of confidence, that recent increases in global temperature are primarily anthropogenic in origin, attributable in the main, but not solely, to the burning of fossil fuels. Much has been written about strategies of mitigation of these emissions, and/or adaptation to the higher temperatures that will ensue if we extrapolate according to their present rate of growth.

In this article, we study the problem of intergenerational equity in a world that is constrained to limit GHG emissions in order to keep global temperature at an acceptably low level. We construct and calibrate a dynamic model involving economic and environmental variables. We eschew the specification of a physical model of emission-stock interactions, and consider instead a particular path for the environmental variables, which entails low emissions after 2050, and realistically appears to be feasible given present knowledge of climate dynamics. The economic variables are then endogenous in our optimization program. We develop a computational algorithm based on the turnpike property, and compute paths of resource allocation which, in a society which consists of a representative agent for each generation beginning with the present one, optimizes an objective function that sustains growth in human welfare forever, for exogenously specified rates of growth, taken to include zero as one possibility.

We show that positive rates of growth in human welfare are possible, while the first generation experiences a utility level higher than the reference level. The computed paths involve investments in knowledge at noticeably higher levels than in the past: the fraction of labor resources devoted to the creation of knowledge must be doubled, whereas the fractions of labor allocated to consumption and leisure are similar to those of the reference level.

On the other hand, higher growth rates, while also feasible, require substantial increases in the fraction of labor devoted to education. We test for the robustness of the model calibration, and find qualitatively similar results.

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We now summarize what is new about our approach, and how it contrasts with the influential works of William Nordhaus (1991, 1994, 2008a) and Nicholas Stern (2007).

The society in our model consists of an infinite set of generations, each represented by a single agent. The agents' utility function, and the set of feasible paths of resource allocation, are specified as follows.

- The representative agent's utility – welfare, standard of living or quality-of-life function – has four arguments: (i) consumption of a produced commodity, (ii) educated leisure time, which is raw leisure valued by the agent's level of education or skill, (iii) the quality of the biosphere at the time the agent lives, a public good, and (iv) the level, or stock, of human knowledge, a public good.[1]
- There are three production sectors: *commodity production* uses as inputs skilled labor, capital, accumulated human knowledge, biospheric quality, and the level of GHG emissions permitted. The *production of knowledge* is purely labor intensive, using only skilled labor and past knowledge (think corporate research and development, and university research). The *education of children* is purely labor intensive, using only the skilled labor of teachers.
- There are four conduits of intergenerational transmission: capital passes from one generation to the next, after investment and depreciation; knowledge passes in like manner, with depreciation; the stock of biospheric quality augmented by emissions of the present generation passes to the next; and adult teachers educate children who become skilled workers and consumers at the next date.
- One very important function is not explicitly modeled: the evolution of biospheric quality from emissions. One might postulate a law of motion for the process by which biospheric quality at date $t+1$ consists of biospheric quality at date t, partially rejuvenated by natural processes that absorb carbon dioxide, plus the impact of new emissions of GHGs. However, the scientific view on the nature of this law of motion is very much in flux, and so we have elected *not* to imply a false precision by inserting such a law into our model. In place of doing so, we simply take a path of emissions and concomitant atmospheric concentration of carbon dioxide computed from the popular Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC; a previous version was used by the Intergovernmental Panel on Climate Change, 2007, IPCC AR4, Working Group I) which stabilizes the atmospheric concentration at 450 ppm CO_2, and we constrain our production sector not to emit more than is allowed on this path. That is to say: *we do not* optimize over possible paths of future emissions, because we believe the knowledge to do so does not exist at present.
- Our exercise is entirely normative: we choose the path to maximize the utility of the first generation, subject to guaranteeing a rate of growth of utility of g for all future generations. We compute this path for various values of g. The path with $g=0$ we call '*pure sustainability optimization*,' as it sustains human welfare forever at the highest possible level. The paths with $g>0$ we call '*sustainable growth optimization*'. We do not propose a rule for adjudicating among various values of g: but our calculations suggest that values of g of 2% per annum (64% per generation) are more ethically attractive than the optimal path at $g=0$.
- As our approach is purely normative, we do not propose an economic equilibrium model, nor do we attempt to predict what the path would be in the absence of policy (what is often called the *business as usual* path).
- Technological change is modeled by the presence of knowledge, accumulated through investment in R&D, as an input into commodity production. Thus knowledge can substitute for capital, labor, and emissions through the process of technological change.

What is the output of the model which interests us? First, we seek to understand what rates of growth of human welfare can be sustained, given the postulated constraints on emissions. Second, we wish to understand the trade-offs implied by choosing to grow at higher rates: for instance, it turns out to be feasible to support welfare growth of 64% per generation with our calibration, but the cost will be lower welfare for the first generation than it would enjoy under a 0% growth scenario. What is the magnitude of this trade-off? Third, we wish to understand how labor should be allocated among its four uses for various values of g: labor allocated to commodity production, to educating children, to research and knowledge production, and to leisure. Should we radically re-allocate labor from its present uses?

We now contrast our approach to those of Nordhaus (2008a) and Stern (2007).

- Nordhaus (2008a) also carries out a normative exercise of maximizing an intergenerational social welfare function. He does not fix a path of emissions. Instead, he proposes a law of motion of biospheric degradation, and optimizes over not only the paths of consumption, investment, and capital, but also of emissions. As we note in Section 6.2 below, his solution paths entail, for the next two centuries, emission levels substantially higher than the path that we adopt.
- The utility function of his representative agents consists only of consumption of a produced commodity. Accordingly, emissions and biospheric quality affect human welfare only indirectly, through their impact on production.
- Nordhaus proposes an exogenous path of technological change. There is no knowledge-production sector in his model. Neither is there an education sector in Nordhaus (2008a).
- Most importantly, the social welfare function in Nordhaus (2008a) is *discounted utilitarian.* He maximizes the discounted sum of generational utility levels, where the discount rate is calibrated from the rate of time impatience of existing consumers, calculated via the Ramsey equation.
- The Stern (2007) Review does not carry out a full optimization exercise. It compares only two paths: 'business as usual,' against an alternative path that cuts back severely on emissions. The criterion used to compare these two paths is discounted utilitarian. But the objective differs from Nordhaus because Stern chooses a much smaller discount rate (larger discount factor) than Nordhaus. Rather than calibrating the discount rate from the Ramsey equation – and thus from the rate of impatience of market consumers – Stern (2007) discounts future utility only because future generations might not exist, due to a small probability, at each date, of the disappearance of the human species.

There are three principal differences between our work and that of Nordhaus and Stern.

(a) We include four arguments in the utility function, not one. This is more realistic, we believe, and also provides more possibilities for substitution in order to maintain growth of human welfare.[2] But in order to isolate the role of our alternative social welfare criterion (sustainability instead of discounted utilitarianism) from that of our alternative notion of individual welfare (multivariate utility function instead of consumption) we have also performed our analysis substituting consumption for utility while maintaining the sustainability criterion.

(b) Our objective is to sustain the growth of human welfare, at some specified rate of growth, rather than maximizing the discounted sum of generational utilities. We lack the space in the present paper to argue *why* we view our approach as superior: but we refer the reader to extended discussions of

[1] Many utility functions present in the literature include one or several of these arguments. Environmental amenities, in particular, often appear as arguments in natural resource models, see, e. g., Jeffrey Krautkraemer (1985).

[2] While Nordhaus (2008a) claims that his 'consumption' can be interpreted as including myriad goods, this is incorrect. For the production of different goods (leisure, education, knowledge) impact very differently upon biospheric quality through their emission of GHGs. Nordhaus's aggregation would be valid only if all relevant goods impacted upon biospheric quality in the same way.