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North–south convergence and the allocation of CO_2 emissions

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Abstract

Mankind must cooperate to reduce GHG emissions to prevent a catastrophic rise in global temperature. How can the costs of reducing GHG emissions be allocated across regions of the world and simultaneously address growth? We postulate a two-region world and, based on sustainability and egalitarian criteria, calculate optimal paths in which a South, like China, and a North, like the United States, converge in welfare per capita to a path of sustained growth of 1 % per year by 2085, while global CO_2 emissions are restricted to a conservative path, constructed from the Representative Concentration Pathway RCP3-PD scenario, that leads to the stabilization of concentrations around 450 ppm CO_2, providing an expected temperature change not exceeding 2 °C. It follows from our analysis that growth expectations in the North and the South should be scaled back substantially, not only after 2085, but also in the transition period. Feasible growth paths with low levels of emissions would require heavy investments in education and knowledge. Northern and Southern growth should be restricted to about 1 % and

2.5 % per year, respectively, over the next 75 years. Politicians who wish to solve the global-warming problem should prepare their polities to accept this reality.

Electronic supplementary material

The online version of this article (doi:10.1007/s10584-014-1227-8) contains supplementary material, which is available to authorized users.

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1 Introduction

Two questions must be answered for a successful attack on the problem of global warming:

(i) what is the time path of global emissions of greenhouse gases (GHG) that should be set as the target in order to approximately stabilize the concentration of carbon in the atmosphere at an acceptably low level, and

(ii) how should this budget of total emissions be allocated to the regions of the world, and simultaneously address growth. Both issues are contentious.

This paper assumes that question (i) has been answered. We assume a non-overlapping-generations model, where each generation lives for 25 years, and rely on the Representative Concentration Pathways (RCP), a set of consistent projections of the components of radiative forcing extending until 2100 prepared for the IPCC’s Fifth Assessment Report (AR5).[1] In particular, we adopt a path for CO_2 emissions based on RCP3-PD (a.k.a. RCP2.6), the only RCP that provides an expected temperature change not exceeding 2 °C and is representative of scenarios of very low concentration levels. Its radiative forcing level first peaks at 3.1W/m^2 in the middle of the century and then returns to 2.6W/m^2 by 2100, thus its name: “Peak & Decline” (van Vuuren *et al. 2007*; van Vuuren *et al. 2011*). Our setting requires constant annual emissions within a generation as well as stabilized emissions and concentration after year 2060. Hence we adapt the emissions in RCP3-PD to these requirements and run them in MAGICC 6.4. Figure 1 pictures our Generational Path. CO_2 concentration stabilizes at around 460 ppm, while the expected temperature increase stabilizes below 2 °C.[2]

Emissions of fossil CO2

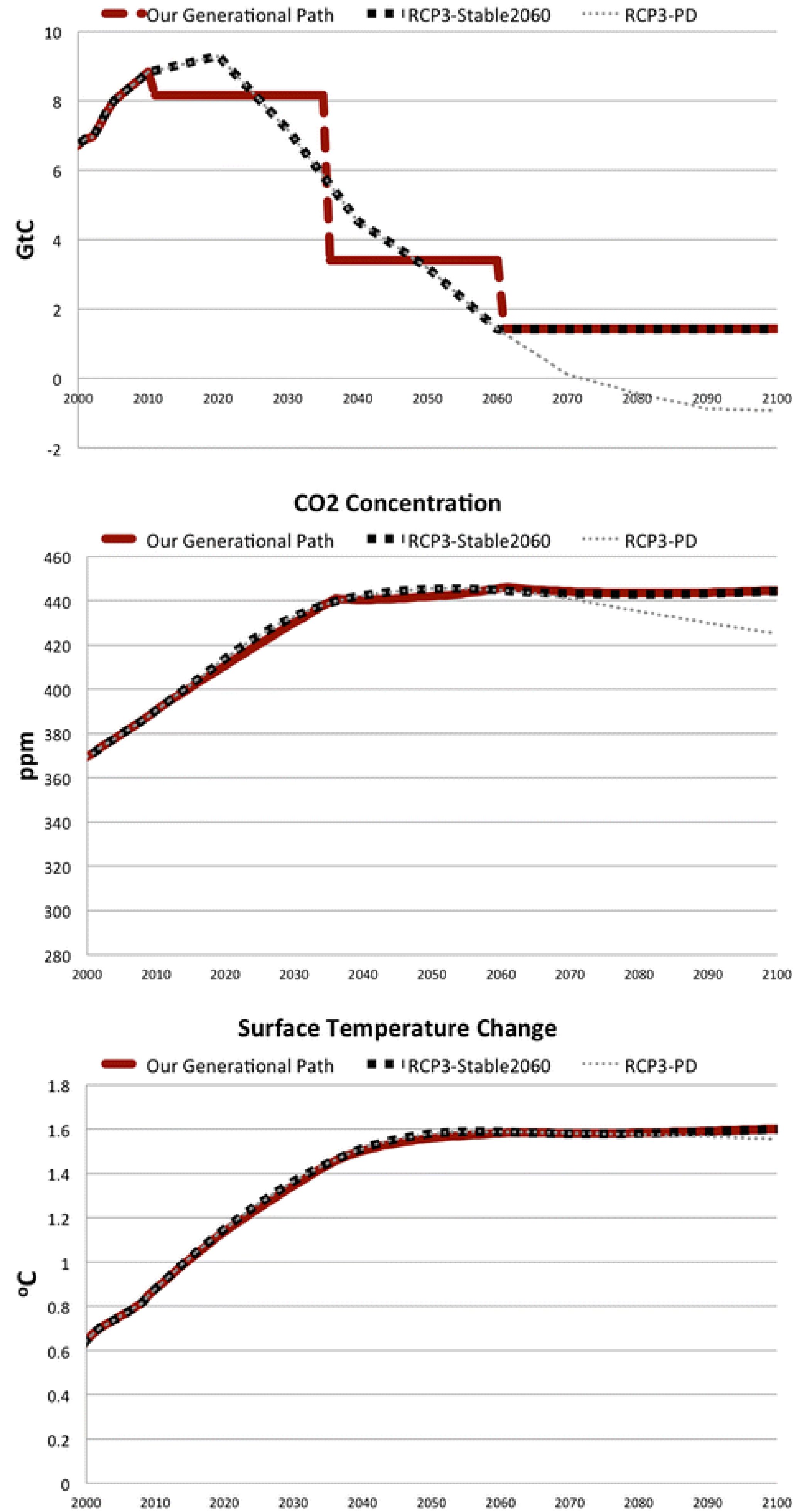
Our Generational Path
RCP3-Stable2060
RCP3-PD
GtC
10
8
6
4
2
0
-2
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
CO2 Concentration
Our Generational Path
RCP3-Stable2060
RCP3-PD
ppm
460
440
420
400
380
360
340
320
300
280
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Surface Temperature Change
Our Generational Path
RCP3-Stable2060
RCP3-PD
°C
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100

Fig. 1

Emissions, concentrations and temperature change. Each graph plots together three paths: the original RCP3-PD; *RCP3-stable2060*, which only differs from RCP3-PD by stabilizing emissions after 2060; and our *Generational Path*, which assigns to each generation its average annual emissions according to *RCP3-stable2060*. CO_2 concentrations and temperature changes are obtained by running MAGICC 6.4 for each of the three emissions paths

This paper addresses question (ii). We assume that all countries, developed and less developed, must share in the effort to reduce GHG emissions. Our method is optimization in a calibrated generational model. The logic of our analysis can be extended to a multi-region world, but, for the sake of simplicity, we consider one comprised of only two regions, North and South, which are populated by representative households in each region and generation. (Population size is addressed below.) North is postulated to have the level of economic development of the United States, and South that of China. Our analysis is purely normative. The plan that we propose obeys the welfare criteria explained in the following section, which are grounded in the Rawlsian, maximin approach instead of the discounted utilitarianism commonly used in climate change economics and integrated assessment models. We do not address the complex and separate issue of implementing the plan that we propose: we take the viewpoint that setting targets must precede implementation.

Any analysis attempting to capture the complex problem of climate change must ignore some features of reality. We list what we believe are the main caveats for ours. First, we ignore uncertainty. Second, we neglect natural-resource constraints other than GHG emissions.[3] Third, we postulate a Cobb-Douglas production function, implying a unity elasticity of substitution between environmental and economic inputs. Fourth, we take the Cobb-Douglas parameters to be the same for the US and China, so that the initial technological differences are due to the dissimilarity of their endowments in human capital and in knowledge (see Section 3 below). Accordingly, our analysis has the character of a thought exercise, and its validity is contingent to the real-life significance of these limitations.

2 Normative stance and optimization

2.1 Desiderata and constraints

We look for paths of region-by-region emissions and all economic variables that satisfy the following normative desiderata:

(Sus) sustainability

(Eg) egalitarianism

(Con) convergence, and

(Eff) efficiency.

We adopt particular formulations of these desiderata. For (**Sus**), we focus on the sustainable growth of human welfare, and we explore the maximal sustainable growth rate, see Section 2.2 below. Egalitarianism, (**Eg**), motivates, on the one hand (**Con**), the long run equality of welfare in North and South, and, on the other, a Rawlsian focus on the welfare of the South in the short run, where the world's worst-off generations live. As for (**Con**), we require North and South's welfare per capita to converge in several generations.

We adopt four types of constraint:

First. The usual resource and technology feasibility constraints;

Second. That world emissions follow the postulated low-emission path stabilizing expected temperature increase below 2 °C;

Third. That North and South converge in welfare per capita (and, indeed, in consumption per capita) in three generations (75 years);

Fourth. That the rate of intergenerational welfare growth, in North and South, be no lower than an exogenously specified rate, ϱ.

The choice of three generations for the date of convergence is reasonable, yet to some extent arbitrary. Imposing convergence in less than three generations would be unnatural. For the purposes of testing the robustness of our results, we have performed our analysis imposing convergence in four generations instead, with little change in the qualitative results.

Significantly, our analysis addresses the *critical issue of the existence of feasible paths that satisfy desiderata* (**Sus**), (**Eg**), (**Con**) and (**Eff**). In particular, by repeating the optimization for various values of ϱ, our method discovers how much growth is consistent with a successful resolution of the climate-change problem in line with our four desiderata.

Among the feasible paths we choose an optimal one. We calculate two versions of the objective function (i. e., of what is to be maximized):

Version 1. The true maximin path: maximize the utility of the worst-off generation in the world, namely Generation 1 in South.

Version 2. Maximize the utility of Generation 2 in South, the second worst-off generation (see Section 4 below).

A precise formulation of our optimization program will be given after the formal definition of sustainability in Section 2.2 below.

Economic efficiency (**Eff**) is reached by virtue of optimization under either version.

2.2 Sustainability

Our guiding ethic is the sustainability of human welfare over time.[4] Consider, first, a simpler world, with only one region, inhabited by one representative household at each period (generation), indexed by $t = 1, 2, \ldots$. Consider two interpretations of sustainability.[5] The first, *pure sustainability,* finds the highest level of welfare that can be sustained for all generations. Denote by u_t the utility (welfare) of the t-period household. Let U be the set of utility paths $u = (u_1, u_2, \ldots)$ which can be achieved, given current endowments and technology, and constraining economic activity to stay on a given path of carbon emissions. Pure sustainability directs us to solve the program:

$$\begin{aligned} &\max \Lambda \qquad \text{subject to} \\ &\quad u \in U, \\ &\quad u_t \geq \Lambda, \quad t \geq 1. \end{aligned} \tag{[1]}$$

Its ethical justification is that the period at which a person is born is morally arbitrary, and so each generation is *entitled* to as much welfare as each other generation.

Nevertheless, humans may value the possibility of rendering future generations better off than themselves, and may decide not to enforce this entitlement. Let $\varrho > 0$ be a rate of welfare growth. Then *sustaining growth* at some fixed value of ϱ directs us to solve the program:

$$\begin{aligned} &\max \Lambda \qquad \text{subject to} \\ &\quad u \in U, \\ &\quad u_t \geq \left(1 + \rho\right)^{t-1} \Lambda, \quad t \geq 1. \end{aligned} \tag{[2]}$$

Our *sustainabilitarian* approach to climate change contrasts with the conventional view exemplified by Nordhaus (*2008*, *2013*) and Stern (*2007*), for which the maximization objective is a discounted sum of future utilities.

Central to the analysis by discounted utilitarians is the choice of the discount rate. Nordhaus chooses that rate to reflect the time preferences of present-generation consumers and investors, as expressed in financial markets. Stern chooses the discount rate to reflect the probability of extinction of the human species at some future date. Stern's discount rate is substantially smaller than Nordhaus's, which leads him to recommend more severe reductions in emissions. We object to Nordhaus's choice of discount rate, because we do not believe that the time preference of the current generation is *ethically* relevant for allocating resources across generations. We agree with Stern that uncertainties about the existence of future generations are relevant for the problem, but we advocate our sustainabilitarian approach over his utilitarian approach.[6]

The application of the sustainabilitarian approach to a world with two regions is based upon a turnpike theorem proved in Llavador et al. (*2010*). In the fleshed-out economic model of which programs [1] and [2] are abstract versions, there is an economy that begins with a vector of endowments of physical and human capital. A path of emissions is given that converges to the desired atmospheric concentration: not exceeding the emissions on this path yields one set of constraints defining the set U. Emissions are generated by the production of commodities used for consumption and investment. By the turnpike theorem, if emissions are constant at e^* per capita and population is constant, such as to maintain a constant level S^{m*} of atmospheric carbon concentration, and if ϱ is sufficiently small, then there exists a ray $\Gamma(\varrho, e^*, S^{m*}) \subset \Re_+{}^2$ such that, should the initial endowment vector lie upon the ray, then a solution to Program [2] exists with the property that all economic variables (investment, capital stock, consumption, education, labor expended in three sectors, etc.) grow forever at a fixed rate slightly larger than ϱ.[7] The turnpike theorem further asserts that if the initial endowment vector does not lie upon this ray, then the optimal solution to the program converges to the ray, and hence eventually enjoys (approximately) balanced growth.

Accordingly, we model the problem of North–South emissions allocation as one where the Northern and Southern representative households begin with different endowments, and we study the paths of resource use under which both representative agents converge to the same point on the ray $\Gamma(\varrho, e^*, S^{m*})$ in 75 years: the assumption is that both economies then enjoy balanced growth (at the rate ϱ of generational welfare).

We ask: what is the largest value of ϱ for which *feasible* paths exist? A central result of the analysis is that feasible growth paths exist satisfying the constraints delineated in Section 2.1 if and only if the value of ϱ is less than 1.11 % per year (equivalently, 32.1 % per generation) over the next 75 years. This is considerably less than what growth would be at the conventional 2 % per annum rate (64.1 % per generation). Correspondingly, the growth rate of South must be reduced from conventional projections as well. In other words, we believe that growth expectations in North and South must be scaled back substantially for global greenhouse-gas-emissions negotiations to succeed. It is important to note that no *feasible* path exists satisfying the four constraints of Section 2.1 for values of ϱ greater than or equal to 1.11 %. This statement is independent of what objective function is chosen –thus, our sustainabilitarian objective is only one way of choosing an optimal path from this feasible set. Our analysis implies that politicians who wish to solve the global-warming problem should prepare their polities to accept this reality of slower growth.

3 The model

We extend the model for a single US household constructed in Llavador et al. (*2011*) to the two-region world of this study. We describe it verbally in the text; all precise specifications of optimization programs, parameter values, and description of estimation procedures are found in the (online) Appendix.

The economy possesses three production sectors: the production of output (which aggregates all types of commodities), the education of the next generation, and knowledge production (R&D, the arts, science, etc.). Output is produced from inputs of knowledge, educated (skilled) labor, capital, emissions, and biospheric quality, combined in a Cobb-Douglas technology exhibiting constant returns to scale in skilled labor, knowledge, and capital. Treating emissions as an input formalizes the idea that the larger the emissions of a firm, the more output can be produced, holding other inputs constant. Emissions, of course, affect GHG concentrations.

For simplicity, we adopt the same parameters of the Cobb-Douglas production function in North and South, describing how the inputs of knowledge, skilled labor, and capital are converted into output.[8] Nevertheless, because the endowments of knowledge, the levels of skill, the stock of capital and emissions are very different in the two regions, the marginal products will also be very different. Indeed, our calibration yields that the marginal product (or productivity) of labor in North is eight times that in South in 2010, our reference year.[9]

Education uses a linear, labor-intensive technology: the skill embodied in the young generation is proportional to the time the older generation allots to teaching, and to the older generation's own skill (i. e., education) level.

Knowledge is produced also using labor as the only input: knowledge in North in period $t + 1$ equals knowledge in North in period t, depreciated by a certain factor, plus a term proportional to the labor employed in the knowledge sector. South can benefit from knowledge diffusion as long as North has more knowledge than South (Eaton and Kortum *1999*; Keller *2004*). Knowledge in South depreciates at a certain rate and increases by new knowledge produced by knowledge workers in South plus the knowledge diffused from North. This diffusion depends on the knowledge gap between North and South and also on the level of employment of knowledge workers in South, the so-called Nelson-Phelps technological catch-up hypothesis (Nelson and Phelps *1966*; Benhabib and Spiegel *2005*).

Consequently, labor in each period is partitioned into four uses in each region: its employment in the three sectors, plus leisure.[10] Capital in period $t + 1$ equals depreciated capital from period t plus investment. Output is partitioned into consumption, investment and exports. Note that the only sector that emits CO_2 is the production of output. Thus, beginning with endowments of human capital, physical capital, knowledge and atmospheric carbon concentration inherited from period t, there will be, as a result of production in period $t+1$, new endowments of human capital, physical capital, knowledge, and atmospheric carbon concentration to pass on to Generation $t+2$.

Human welfare, or utility, is a Cobb-Douglas function of four arguments: commodity consumption, educated leisure, the stock of human knowledge, and GHG concentrations.[11] Putting *educated* leisure rather than raw leisure time in the utility function models the view that education increases the possible uses of leisure time, and therefore increases utility. Making the stock of human knowledge an argument models the idea that people are curious, take pleasure from the arts, and have a quest to understand the world. Knowledge is a public good –it is not associated with an individual's level of education. (We value our collective possession of knowledge, even if we cannot access all of it personally.) Educated leisure and knowledge also serve as proxies for the health level. It is salient that GHG concentrations, knowledge, and education enter both the commodity production function and the utility function.

Modeling utility as a function of these four arguments is unusual in climate-change economics, whose practitioners frequently take utility to be a function of consumption only (Nordhaus *2008*; Stern *2007*). We believe this practice is too narrow in not appreciating the *direct* value to humans of education, knowledge and a non-carbon-polluted atmosphere (Llavador et al. *2013*). These arguments are *not solely* important because of their usefulness in commodity production.[12]

As noted, date 0 is taken as 2010, and a generation is understood to live for 25 years. Populations of the global North and South follow United Nations (*2013*) projections, stabilizing at ten billion people after 2060.

The parameters in the three production functions and the utility function are calibrated using US historical data. As noted, what differ between the regions are the initial endowments in 2010, estimated from standard sources.

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4 Results

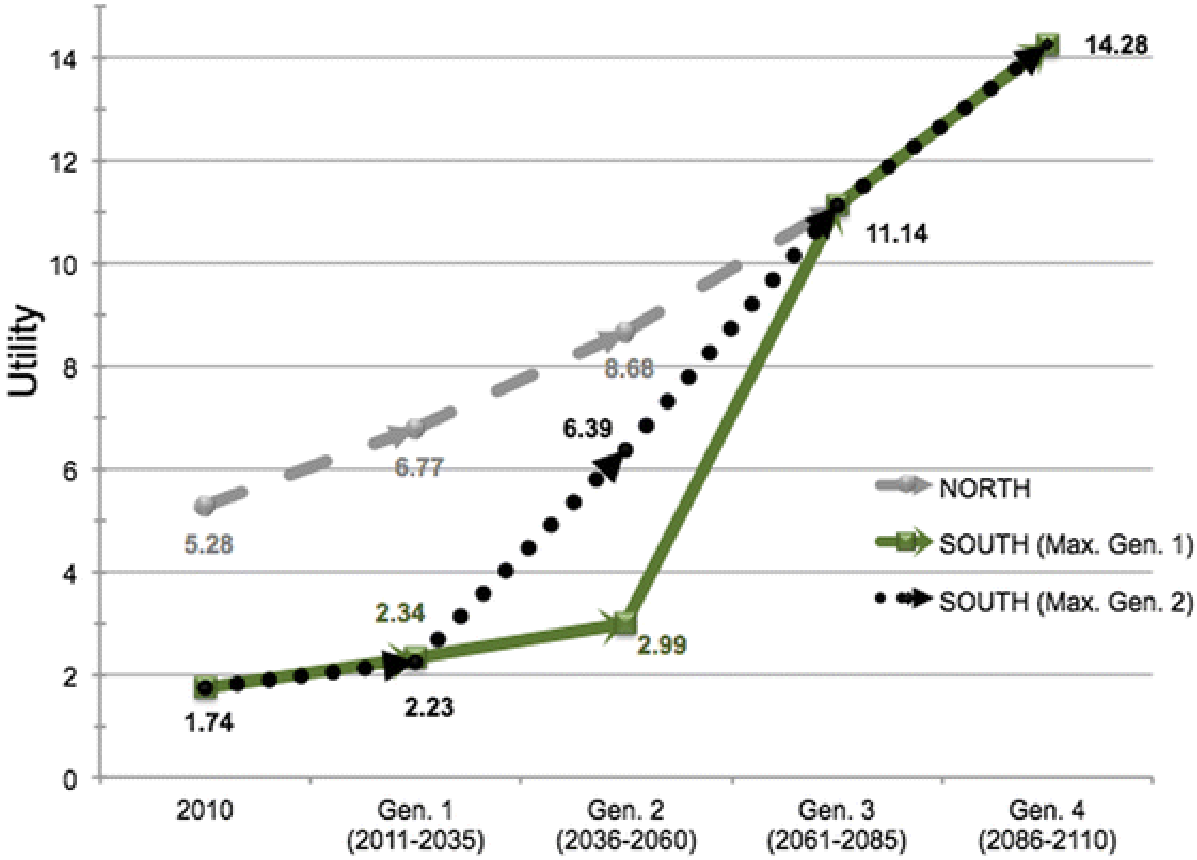
The optimal paths are computed using the 'NMaximize' routine in *Mathematica* 8. Recall that the allocations of global emissions to the two regions in each period are endogenous to the solution of the program. After convergence occurs, in Generation 3, emissions *per capita* in the two regions will be equal forever. In addition, investments in knowledge are endogenous, and it is the level of knowledge that determines technological improvements in commodity production.

Main result

It is possible to sustain a rate of utility growth of 1 % per year, starting from the $t = 0$ (year 2010) reference level, with North and South converging in 75 years ($t = 3$), while keeping global CO_2 emissions at the low levels displayed in Fig. 1 above (which are based on the RCP3-PD path up to 2060, and stay constant thereafter). At convergence, North and South reach a common steady state where all economic variables grow at a constant rate. In particular, the per capita levels of the stock of knowledge, investment in knowledge and emissions are then equalized across regions. During the transition, Northern utility grows at 1 % per year and after convergence, both regions grow at that rate forever.[13]

However, there are no feasible solutions to the program at which both North and South grow at sustainable rates much higher than 1.1 % per year.

Figure 2 depicts three utility paths; $t = 0$ provides the 2010 reference data. The transition generations are $t = 1, 2$; the steady state is reached at $t = 3$ and continues forever at the constant growth rate. The dashed line is North's utility path: its utility grows at 28.2 % per generation (1 % per year) for either objective function. South's optimal path is given by the solid line if we maximize the utility of Generation 1 in South, and by the dotted line if we maximize the utility of Generation 2 in South. The reason for maximizing the utility of Generation 2 in South, instead of applying the strict maxi-min principle (which would dictate maximizing the utility of Generation 1) is now clear: maximizing the utility of Generation 2 in South permits a large increase in that generation's welfare, at the cost of a very small reduction in the utility of Generation 1.



	INITIAL	TRANSITION		STEADY STATE	
	t=0	t=1	t=2	t=3	t=4
North u_t^N	5.2798= u_0^N	6.7710=1.2824 u_0^N	8.6833=1.2824 u_1^N	11.1358=1.2824 u_2^N	14.2808=1.2824 u_3^N
South u_t^S (Max. Gen. 1)	1.7357= u_0^S	2.3351=1.3454 u_0^S	2.9947=1.2824 u_1^S	11.1358=3.7186 u_2^S	14.2808=1.2824 u_3^S
South u_t^S (Max. Gen. 2)	1.7357= u_0^S	2.2259=1.2824 u_0^S	6.3864=2.8691 u_1^S	11.1358=1.7437 u_2^S	14.2808=1.2824 u_3^S

Fig. 2

Utility paths for a guaranteed growth rate of 1 % per year (28.24 % per generation)

We have computed that, subject to the previous constraints on convergence and sustainability, the highest growth rate than can be sustained for all generations in all regions is below 1.12 % per year. Higher steady-state growth rates could in principle be reached if we allowed for lower growth rates in North during the transition. Our computations lead to the conclusion that reaching a convergent steady state with growth rates distinctly higher than 1 % per year would not be possible unless a transition generation in North or South grew at less than the target rate.

As noted, our time paths have two distinct stages: the transition ($t = 1, 2$) and the steady state ($t \geq 3$). The steady state requires North and South to have the same emissions-to-output ratio and the same emissions per capita, whereas initially ($t = 0$, year 2010), North has a lower emissions-to-output ratio, and higher emissions per capita, than South.

Figure 3 displays the optimal values for the allocation of emissions. Recall that our postulated path requires steady-state global emissions to drop to a 16 % of initial values; accordingly, both emissions per capita and the emissions-to-output ratio (“GHG intensity,” in IPCC parlance) must eventually decrease. The initial emissions per capita in North are 3.4 times as large as those in South (Table s.8 in the Appendix), whereas the initial emissions-to-output ratio in South is 1.6 times that of North. All per capita values are equalized in the steady state, including emissions per capita and emissions-to-output ratios.

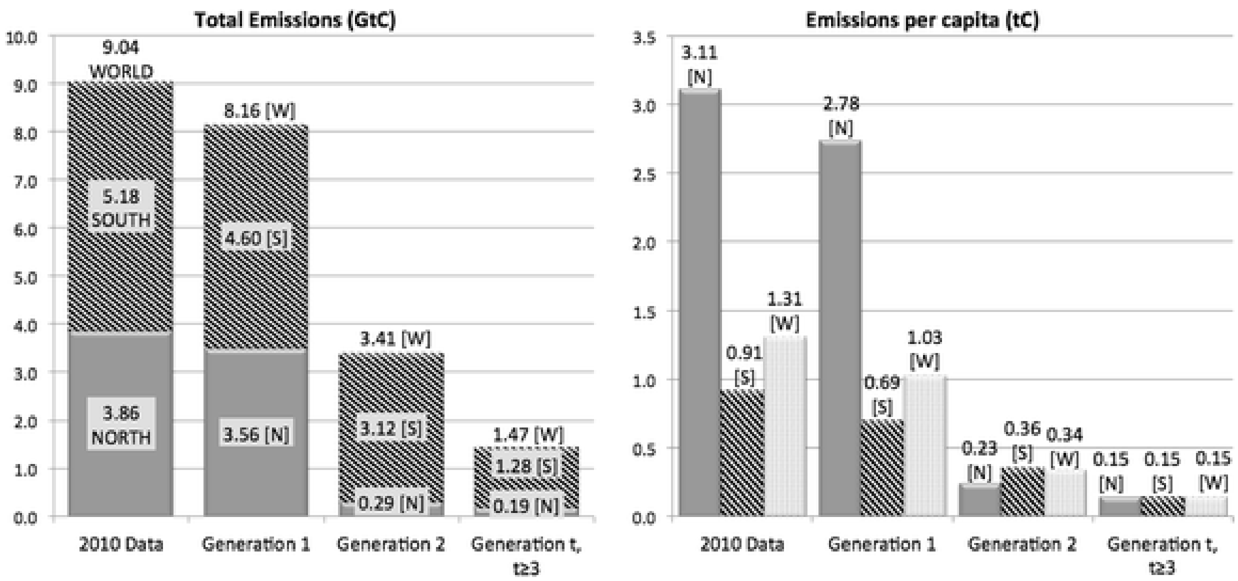


Fig. 3

Total and per capita annual CO_2 emissions (North, South and World). Year 2010 values from World Resources Institute (*2013*)

The steady-state values display the following features.[14]

- Both North and South devote to investment in physical capital 6.8 % of their labor-leisure resource, a Fig. 70 % higher than the reference value of 4 % in North, but substantially lower than the reference 16 % in South.
- In North (resp., South), the fraction of the labor-leisure resource devoted to knowledge in the steady state is almost twice (resp., three and a half times) that of the reference year. And in the steady state South devotes to education a fraction of the labor-leisure resource 48 % higher than the reference level.
- The fractions of the labor-leisure resource devoted to leisure as well as those devoted to the production of output in either region do not substantially differ from the reference values. The same observation applies to consumption in North. But South devotes to

consumption (resp. investment) a fraction of its labor-leisure resource 42 % higher (resp. 44 % lower) than the reference value. This is unsurprising and consistent with the observation, often made, that China is investing too much and consuming too little.

Recall that our notion of output aggregates all kinds of commodities, without differentiation among those produced in North or South. We say that a region *exports* output, in net terms, when its aggregate consumption is lower than its production of output. Net exports are zero after convergence, but the initial 2010 data display net output exports from South to North amounting to 3.2 % (resp. 2.7 %) of South's (resp. North's) output, which are balanced by South's claims on North's assets, not captured by our model.[15]

During the transition, the optimal path entails net exports from North to South at on the order of 5.1 % (resp. 3.8 %) of the output of South (resp. North), and, at $t = 2$, net exports from South to North amounting to 7.6 % (resp. 75 %) of the output of South (resp. North), i. e., the amount imported by North is three fourths of North's own domestic output, admittedly a large figure. Intuitively, who produces what goods and how emissions are allocated is decided entirely by optimization, with emissions and the production of output efficiently allocated. Hence, the marginal product of emissions, and accordingly the emissions-to-output ratios, must be equalized across the two regions. This requires a relatively small allocation of emissions to North at $t = 2$. The sacrifice by North is counterbalanced by South-to-North exports in order to satisfy the constraint that North's utility grow at an annual rate of at least 1 %.

Doubtless, political concerns would restrict the size of trade imbalances. To address this issue, we have computed the optimal paths under the additional extreme constraint of zero net exports, see Section S.6.5 in the Appendix. The qualitative results are unaffected, showing their robustness with respect to the inclusion of this constraint. But efficiency, Desideratum (**Eff**) of Section 1 above, is lost: the utility of Generation 2 in South drops by 5 %, all other utilities remaining at the same levels.

The marginal product of emissions in terms of output implies a shadow price of carbon. For Generation 1, the marginal product of emissions in output is $2,323 per metric ton of carbon or $633 per metric ton of CO_2. This is substantially higher than other policy proposals for the US (see e. g., Table 5-4 in Nordhaus *2008*).

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5 Conclusion

Our analysis displays the following characteristics.

F1 We motivate optimization by the concept of sustaining growth of human welfare, rather than maximizing a sum of discounted utilities over generations (as in Stern *2007* and Nordhaus *2008*).

F2 We specify a global emissions path constructed from the RCP3-PD with an expected temperature change not exceeding 2 °C. We emphasize that the regional allocation of actual emissions is given as part of the optimal solution, rather than being decided a priori based on historical considerations. That is to say, we close the model by appending the constraint of convergence in three generations, and derive regional emissions as a corollary.

F3 We include education and knowledge in the utility function, as well as in the production function. This is psychologically realistic and enables conservation on emissions by shifting to some degree resources from commodity consumption to education and knowledge.

F4 We endogenize technical progress, as determined by the investment in knowledge. This contrasts, for example, with Nordhaus (*2008*), in which exogenous, costless technical progress is postulated.

Modulo the caveats expressed in Section 1 above, notably concerning the calibration of the Chinese economy, our analysis supports the following policy recommendations.

R1 International negotiators should acknowledge the intimate relationship between emissions control and economic growth, and simultaneously address both issues in bargaining venues.

R2 Accordingly, Northern politicians should prepare their citizens for the necessity of curbing growth to 1 % per year. Similarly, Southern politicians should prepare their citizenries to accept growth rates substantially lower than are currently expressed as targets.[16] Of course, if our calibration of the Chinese economy is too optimistic, then even these modest growth rates could not be obtained while satisfying the four desiderata of Section 3.

R3 Both North and South should heavily invest in education and knowledge beyond the current levels, both in the transition and in the more distant future.

R4 The price of carbon should be substantially higher than what has been observed in recent permit markets.

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Electronic supplementary material

Below is the link to the electronic supplementary material.

ESM 1
(PDF 4073 kb)

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Footnotes

1 The RCPs are described in the 2011 special issue of *Climatic Change*. For a summary see Meinshausen *et al*. (*2011*) and van Vuuren *et al*. (*2011*). The data can be obtained from http://www.pik-potsdam.de/%7Emmalte/rcps.

2 The corresponding levels in RCP3-PD are more conservative, since negative emissions after 2073 stabilize CO_2 concentrations at around 375 ppm and expected surface temperature increase at around 1.2 °C. See Section S.3.2.5 of the (online) Appendix for a detailed description of our Generational Path with extended projections until the year 2500.

3 These are no doubt important (Arrow et al. *2004*, Barnosky et al. *2012*, and Vitousek et al. *1997*).

4 In other contexts, sustainability applies to maintaining some index of natural resources (Neumayer *2013*).

Here we follow Solow's (*1993*): "I will assume that a sustainable path for the national economy is one that allows every future generation the option of being as well off as its predecessors" (p.168).

5 See Llavador et al. (2011, 2013) and Roemer (*2011*).

6 Although we do not explicitly consider here Stern's kind of uncertainty, it can be proved that, as long as the probability of extinction is not too large, our formulation is mathematically equivalent to one in which uncertainty is explicitly modeled (Llavador et al. 2010, 2011, 2013; Roemer *2011*).

7 Since utility must grow at rate ρ, and one of the arguments of the utility function is essentially fixed (atmospheric carbon concentration), the other arguments must grow at a slightly higher rate than ρ.

8 Starting with different parameters for each region would require postulating a law of motion for these parameters so that they eventually converge. We do model the spillover of knowledge from North to South, but we feel that attempts to extend the approach to the parameters of the production function would be ad hoc.

9 North's marginal products of capital and emissions are respectively about 1.7 and 1.6 times those in South (Section S.3.2.7 in the Appendix). The marginal product of an input is the rate at which output increases instantaneously as the amount of the input is increased, holding other inputs constant. For the Cobb-Douglas production function, this rate is proportional to the output–input ratio.

10 We assume that no resource is wasted; in particular, there is no involuntary unemployment.

11 Precisely: utility in period *t* is $c_t^{\alpha_c}\left(x_t^l\right)^{\alpha_l}\left(S_t^n\right)^{\alpha_n}\left(\widehat{S}^m - S_t^m\right)^{\alpha_m}$, where $\left(c_t, x_t^l, S_t^n, \widehat{S}^m - S_t^m\right)$ are consumption, leisure in units of skill, the stock of knowledge, and the non-carbon-polluted atmosphere, respectively, in period *t*. The four α_j exponents are positive and sum to one.

12 Llavador et al. (*2013*) performs the exercise of identifying utility with consumption only, instead of the four-argument utility function, in a one-region world. The feasibility of sustaining annual growth rates around 1 % is robust to this modification but, of course, the paths for the economic variables are quite different.

13 Not surprisingly, in order to catch up with North, South's consumption of output has to grow fast during the transition, see Section S.4 in the Appendix.

14 Values for the economic variables along the transition and in the steady state are reported in section S.4 of the Appendix.

15 See Table s.12 in the Appendix.

16 This recommendation is in line with those put forth by Skidelsky and Skidelsky (*2012*), Gordon (*2012*) and Rogoff (*2012*), who call for limiting growth based on different considerations.