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SYMPOSIUM

Unspoken ethical issues in the climate affair: Insights from a theoretical analysis of negotiation mandates

Franck Lecocq · Jean-Charles Hourcade

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Abstract Taking climate change as an example, this paper provides new insights on the optimal provision of a long-term public good within and across generations. We write the Bowen–Lindhal–Samuelson (BLS) conditions for the optimal provision of the public good in a world divided into *N* countries, with two periods, present and future, and we simultaneously determine the optimal response in the first and second periods for a given rate of pure time preference. However, the Negishi weights at second period cannot be determined unambiguously, even under a "no redistribution constraint" within each generation, because they depend on non-observable future incomes; and thus on the answers to two often-overlooked ethical questions: (i) Do rich countries agree on deals which recognize that developing countries may catch up with developed countries in the long run, or do they use their negotiating powers to preserve the current balance of power? And (ii) does each country consider only the welfare of its own future citizens (dynastic solidarity) or does it extend its concern to all future human beings (universal solidarity)? Answers to (i) and (ii)—critical in the

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F. Lecocq (✉)
AgroParisTech, Engref UMR 356 Economie Forestière, 54000 Nancy, France
e-mail: franck.lecocq@nancy-engref.inra.fr

F. Lecocq
INRA, UMR 356 Economie Forestière, 54000 Nancy, France

J.-C. Hourcade
Centre International de Recherche sur l'Environnement et le Développement,
Nogent/Marne, France

debate about how to correct the market failures causing global warming—define four sets of Negishi weights and intertemporal welfare functions, which we interpret as four mandates that countries could give to the Chair of an international negotiation on climate change to find an optimal solution. We find that in all mandates, public good provision expenditures are decreasing functions of income at first period. But each mandate leads to a different allocation of expenditures at second period and to different optimal levels of public good provision at both first and second periods. Finally, we show that only one of these four mandates defines a space for viable compromises.

Keywords Public goods · Inter and intra generational equity · Negishi weights · Climate change

JEL Classification D63 · D78 · H41 · Q54

0 Introduction

Besides controversies about the seriousness of the climatic threat, conflicting perceptions of equity between developed and developing countries are a key reason why, after Copenhagen, the international climate regime remains as "unfinished business" as ever (Jacoby et al. 1998). An archetypal exchange between the G77 and the US in Kyoto sums up the controversy over who should pay for climate mitigation. "There will be no agreement […] until the question of emissions rights is addressed equitably", stated the G77 and China during the conference, mere months after the US Senate had unanimously voted that it would not ratify any Protocol without "meaningful participation" of developing countries (Bird–Hagel resolution, July 1997).

This debate presupposes that climate mitigation constitutes a *burden* to be shared among countries (an assumption we come back to later). Yet remarkably, it has mostly been framed around *ethical intuitions* about what is fair—intuitions only loosely connected to economic principles, if at all. Two such major intuitions are per capita allocation of emission rights (Agarwal and Narain 1991) which many developing countries support and its polar opposite grandfathering which underlies the position of many developed countries.[1] The principle of "common but differentiated responsibilities" of the UN Framework Convention on Climate Change (UNFCCC, art.4) is a rhetorical compromise between these two views, but it has no operational content per se (Stone 2004).[2]

Searching for such guidance, one strand of the literature adopts the point of view of the theory of justice (e.g., Posner and Sunstein 2009; Helm and Simonis 2001; Godard

[1] The ethical justification of grandfathering is the absence of retroactive responsibility for decisions made before the reformulation of the international social contract by the climate regime.

[2] In fact, UNFCCC art.4 and the Kyoto Protocol did provide a practical translation of the "common but differentiated principle" by setting up emission targets for developed countries only (art.4.2), on the ground that "social development and poverty eradication are the first and overriding priorities of the developing countr[ies]" (art.4.7). But deeper emission cuts beyond 2012 require participation of at least major emitters among developing countries. Hence, the renewed debate about who should reduce GHG emissions, and by how much.

2000), but it elevates the debate to a level—the choice between competing views of justice—that is hardly operational. In particular, it provides no clear judgment on pragmatic proposals for negotiating emissions quota.[3] Another strand uses models of the world economy to assess the implications of such rules (see Gupta et al. 2007 for a review). It has helped clarify the stakes for each country (e.g., Lecocq and Crassous 2003) and the rationale of alternative climate regimes (e.g., Aldy and Stavins 2007) but it has so far refrained from delivering statements about the legitimacy of different burden-sharing principles.

The caution of economists in this matter may be a symptom of their professional reflex that "it is useful to separate efficiency from equity" (Goldemberg et al. 1996) since compensating transfers can restore any income distribution judged equitable on pure political grounds. Despite the contribution of Chichilnisky (1993), who showed that the second theorem of welfare does not hold in the presence of an indivisible public good,[4] a continued deficit of economic conversation about equity principles substantially lowers the chances of finding a successor to the Kyoto Protocol. The new cycle of negotiations is indeed more complex than the pre-Kyoto one because, with the emergence of candidate super powers in the Third World, the North/South division is no longer a pure Rich/Poor division boiling down to a distributional issue. In this context, continuing to oppose intuitions about what is 'equitable', 'fair', 'just' or 'balanced' increases the risk of endless, and ultimately self-defeating, verbal jousting with ethics as a rhetoric weapon.

Obviously, the very idea that mitigating climate change constitutes a net social cost is questionable. First, climate policies should provide a net intertemporal social *benefit* by reducing the total climate change bill (i.e., mitigation costs *plus* damages) relative to a world without mitigation but with full damages (Stern 2007; Shalizi and Lecocq 2010). It is thus possible to find Pareto-improving climate policies that make North and South better off (Chichilnisky et al. 2000). As to the fact that climate policies may still constitute a net burden for *early* generations, it can be argued that mitigation could be financed by redirecting investments instead of limiting consumption (Foley 2009; Rezai et al. 2010). And in a second-best world, removing existing barriers to development—e.g., improving energy security, accelerating technical change, or upgrading local environmental quality—may yield both lower emissions and net social benefits. In the remainder of this text, however, we stick to the mainstream view that mitigation constitutes a net social cost at first period (Fisher et al. 2007). Because this may be true for very tight climate targets and once transaction costs of Pareto-improving policies are accounted for, this view still prevails among negotiators, and it leads to ethical misunderstandings that need to be dispelled.

To do so, following Amartya Sen's judgment that "there is something in the methods standardly used in economics, related inter alia with its engineering aspect, that can

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[3] See inter alia multicriteria (Ringius et al. 1998), contraction and convergence (Meyer 2002) or historical responsibilities (Den Elzen et al. 1999).

[4] This insight was further developed in Chichilnisky and Heal (1994), and in Chichilnisky et al. (2000). In a related discussion in this issue, Chipman and Guoqiang (2010) characterize the conditions under which, in a two-individual economy with a polluter and pollutee, the optimal level of pollution is independent of the initial assignment of property rights.

be of use to modern ethics" (1987), we start, rather conventionally, from the social-welfare maximizing benevolent planner metaphor to represent the negotiation about the global public good problem at hand.

We show in Sect. 1 why, given the public good nature of the climate issue (Chichilnisky 1993) this model is a good caricature of the behavior of the Chair of the annual Conference of the Parties to the UNFCCC (COPs) when, on the penultimate day of the conference, she presents a take-or-leave proposal that strives to balance countries' competing demands. In Sect. 2, we show with a two-period model that a conservative but politically realistic no income redistribution constraint and the choice of the rate of pure time preference are not sufficient to fully determine the problem. Two ethical priors, so far overlooked, of the mandates that country delegates impose on the Chair have to be added. The first has to do with countries' attitudes towards the evolving balance of power across nations *over time*. The second has to do with the scope of countries' intergenerational solidarity (future fellow citizens vs. all future human beings).

The remainder of the paper explores the implications of four polar yet plausible mandates deriving from these two dimensions. Section 3 shows that the burden-sharing rule at first period is the same under all four mandates, with, for a large class of utility functions, mitigation costs in proportion of per capita income, whereas Sect. 4 reveals important disparities in the burden sharing at second period. Some mandates appear self-defeating, others are more robust to uncertainty, and all lead to different provisions of greenhouse gas (GHG) abatement at second and at first periods. Illustrative orders of magnitudes are provided with the analytic demonstrations.

1 The benevolent planner model as a metaphor of the negotiation process

The signature of the UNFCCC at Rio de Janeiro in 1992 initiated a very specific negotiation process in which COPs are held annually to design and adopt decisions aimed at fulfilling the overall objective of stabilizing GHG concentrations in the atmosphere.[5]

Consultations amongst parties are conducted all year round in formal and informal settings, but negotiations culminate at the end of each year in the 2 weeks of the COP, where official decisions are adopted. At the start of the COP, draft decisions still contain many bracketed sentences that signal reservations by some Parties. The Chair of the COP acts as a facilitator to delete as many bracketed sentences as possible from the compromise text so that it can be adopted by the general assembly. This role turns out to be crucial when, just before the end of the meeting, the Chair submits a bracket-free package. Country delegates de facto treat it as a take-or-leave proposal because the few amendments they can make in the ultimate hours of the negotiation cannot substantially alter the balance of the package (Grubb et al. 1999).

[5] The Kyoto Protocol was adopted at COP3 in 1997. The 'application decrees' of the Kyoto Protocol were adopted at COP7 (2001). Subsequent COPs like the recent COP15 in Copenhagen have focused on negotiating the post-Kyoto framework.

Of course, an agreement at a COP is not the end of the story. Delegations may accept deals that are subsequently not ratified by their countries' legislative bodies[6] and the obligation that agreements be ratified by a minimum number of countries prior to entry into force can involve additional and lengthy negotiations (8 years for the Kyoto Protocol). However, once an agreement is reached at a COP, individual countries can refuse the deal—and try to prevent its entry into force—, but they cannot significantly modify it. The proposal put forward by the Chair thus remains a pivotal event.[7]

Historical evidence suggests that well-intentioned Chairs tend to put balanced proposals on the table to maximize the chances of acceptance by all countries, even if the proposal is not fully satisfying for each. This exercise is not very far from the program of a benevolent planner who maximizes a social welfare function written so as to translate the implicit mandate passed by the COP on to him or her. This mandate is bounded by political constraints resulting not only from Parties' differing visions of the climate change issue, but also from the existing balance of power between countries.

One such major political constraint is that the benevolent planner can compensate for undue adverse effects of climate policies but is not allowed to redistribute income across countries. This 'no-redistribution' constraint amounts to considering the current distribution of income as a given, something both ethically questionable (Azar 1999) and pragmatically defensible for reasons of political realism: Violating the 'no-redistribution' constraint would be a political non-starter for rich countries, and "it is inappropriate to redress all equity issues through climate change initiatives" (Goldemberg et al. 1996).

In analytical terms, two conditions must be met to satisfy the no-redistribution constraint. First, national contributions to the global mitigation efforts must all be non negative.[8] Second, the weights attached to individual utilities in the social welfare function must be such that the initial distribution of income is welfare maximizing. These weights are unique—up to a scale factor—and equal to the inverse of the marginal utility of income (Negishi 1960). If individual utility functions are logarithmic and if consumptions at different points in time are separable, these 'Negishi weights' are proportional to per capita income.[9]

Controversies about the measurement of GDP (PPP vs. exchange rates) notwithstanding, the Negishi weights can almost unambiguously be determined at first period.

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[6] E.g., Australia and the US after Kyoto. However, Australia has since ratified the Kyoto Protocol (2007). In the US, the House of Representatives passed the American Clean Energy and Security Act of 2009 that would establish an economy-wide, greenhouse gas cap-and-trade system. At the time of writing, the legislation is under debate in the US Senate.

[7] The present paper focuses on the conditions for an international agreement on climate change. Yet, reaching a global agreement is a necessary but not a sufficient condition to effective mitigation as actions at different scales interact (Ostrom 2010).

[8] In the Kyoto Protocol this condition is not met for most economies in transitions which were given more allowances than projected baseline emissions. But this situation results from tactical concessions made during the negotiations, and it is unlikely to be replicated in a post-Kyoto agreement.

[9] Obviously, this results in a very unequal weighting of individual utilities. But were all the weights set to unity instead, the planner would recommend a large-scale, politically unrealistic, redistribution of wealth to achieve the equal per capita distribution of income that would maximize social welfare.

But this is no longer true at subsequent periods because future GDPs are uncertain. It is conventional modeling practice to assume time-varying Negishi weights, so that the *projected* distribution of income is also welfare maximizing at any point in time (e.g., Nordhaus and Yang 1996). But this is a pure modeling artifact which presupposes that the planner is allowed by parties to anticipate changes in world income distribution (typically, a catching-up by poor countries), which is arguably a bold assumption about the political economy of the negotiation.

In fact, "states are cold monsters" (Machiavelli). Thus, the natural reflex of rich countries is to refuse to acknowledge ex ante a decline of their economic and political power [10] and, on the contrary, to use this power to create institutional irreversibilities. Examples abound of long-lasting arrangements (e.g., the composition of the U.N. Security Council, or the distribution of voting shares at the IMF Executive Board before its recent reform) that mirror the balance of bargaining powers at the time they were formed—however dramatically this balance has shifted since then. In climate negotiations, country delegations range from a handful to more than one hundred in size, with a clear correlation between size and wealth, and the Chair necessarily devotes more attention to the most influential delegations at the moment of the final agreement (Grubb et al. 1999).

The key issue for our discussion is that adopting a catch up or a status quo perspective (or any combination thereof) when setting the weights attached to individual utilities at future periods affects the aggregate discounted utility of consumption and thus, for a given rate of pure time preference, influences the trade-off between the short term and the long term. Here, the choice of the weighting matters to determine the Pareto optimum because a public good is considered. Weights would not matter if a private good were considered.

Together with the no-redistribution imperative and attitudes regarding future balances of power, a third issue raised by writing a social welfare function for climate policies lies in the fact that knowing the beliefs of parties about climate change damages does not suffice in characterizing their attitudes vis-à-vis climate change.[11] It is indeed highly likely that damages will be very unevenly distributed across countries, but climate scenarios at the regional level are at least one order of magnitude more uncertain than climate scenarios at the global level. It is thus very hard to predict the extent to which a country will suffer *directly* from climate change. And it is even harder to anticipate how individual countries will be affected *indirectly* from the propagation of impacts in other countries (via, e.g., markets, migration, transboundary impacts, common resource management, etc.). Parties' attitudes vis-à-vis climate change will be very different depending on whether they disregard this uncertainty and take into account only the impacts expected to fall on their future fellow citizens—thus following a sort of *dynastic solidarity* ethics, or take into account the impacts expected to fall

[10] Developed countries may argue that convergence in per capita incomes may not occur, or at least may not *necessarily* occur because of institutional failures in developing countries or of mechanisms leading to poverty traps.

[11] For an overview of the attitudes vis-à-vis climate change damages, see Ambrosi et al. (2003).

on their own future fellow citizens and on *all other* future individuals—thus following a *universal solidarity* ethics.[12]

These ethical attitudes can be translated in the language of optimization by combining them into mandates that shape the social welfare function retained by the benevolent planner. In the real world these mandates will necessarily be a composite function of many types of constraints put forward by the different delegations. However, because our purpose is to clarify the implications of various ethical postures, we will assume that the planner responds to a clear-cut mandate that combines one of two polar attitudes towards distribution of income in the future ('status quo' or 'catch-up'), and one of two polar attitudes towards damages falling on other countries ('dynastic' or 'universal'). This mandate may either reflect consensus amongst parties or the dominant influence of a leading coalition. The rest of the paper will demonstrate how the optimal provision of the public good differs according to the mandate, and that only the catch-up universal mandate defines a space for viable compromise at second period.

2 An analytical framework to capture key ethical issues

We build on Sandler and Smith (1976) intertemporal version of the Bowen-Lindhal-Samuelson (BLS) model of the optimal provision of public goods. The world is divided in N countries, and there are two periods, present and future, the latter indexed by superscript f. At first period, we assume that climate change has no impact yet, and that the representative individual of the l_i inhabitants of country i allocates her income y_i between c_i the consumption of a composite private good chosen as numeraire, and a_i the expenses for GHG emission abatement.

$$y_i = c_i + a_i \tag{1}$$

Let x (resp. x^f) be the amount of GHG emissions abated worldwide relative to business-as-usual. Using $x + x^f$ as an inversed index of GHG atmospheric concentration,[13] we denote $d_i(x + x^f)$ the damages of climate change incurred per capita in country i at second period.[14] Second-period budget equations are thus

$$y_i^f - d_i(x + x^f) = c_i^f + a_i^f \tag{2}$$

[12] We discuss later the ethical rationale and political likelihood of this attitude, which appears in the discourses of many NGOs. For the time being, we treat it as a pure logical possibility. Let us simply underline that the term solidarity is not synonymous with equity. Its Latin root is very suggestive: *solidus* means compact, solid, firm, while *solidarus* means with whom I consider myself to be attached.

[13] Since it ignores the carbon cycle, this index is a simplification of the dynamics of GHG accumulation in the atmosphere, but it is sufficient to capture the stock externality character of climate change.

[14] Damage functions d_i are twice differentiable. Damages are assumed positive ($d_i > 0$), decreasing in the amount of abatement ($d_i' < 0$), but at a diminishing rate ($d_i'' < 0$). Finally, we assume that damages per capita in the absence of abatement remain lower than per capita income ($d_i(0) < y_i^f$).

Assuming that abatement expenditures are used efficiently, we denote $C(x)$ and $C^f(x^f)$ the worldwide abatement cost functions.[15] The total level of abatement at each period is given by

$$\sum_i l_i a_i = C(x) \tag{3}$$

$$\sum_i l_i^f a_i^f = C^f(x^f) \tag{4}$$

To determine an abatement level for each country at both periods[16] the planner maximizes an intertemporal social welfare function W which encapsulates the no-redistribution constraint, attitudes towards distribution of income in the future, and attitudes towards damages falling on other countries. We discuss in turn each of these ethically related parameters.

First, the *no-redistribution constraint* imposes that individual contributions to abatement a_i and a_i^f be non-negative, i.e.,

$$a_i \geq 0 \tag{5}$$

$$a_i^f \geq 0 \tag{6}$$

It also imposes that Negishi weights be attached to individual utilities, so as to force the planner to consider the initial distribution of income as optimal—and thus to avoid that climate policies be the occasion for income redistribution across countries. Let U_i and U_i^f denote the utility of consumption[17] of the present and future representative individual of country i, respectively.[18] The first-period component of W can be written $\sum_i \alpha_i l_i U_i$ with α_i the Negishi weights attached to individual utilities. These weights

[15] Functions C and C^f are twice differentiable, and such that $C > 0, C' > 0, C'' > 0$, and $C(0) = C'(0) = 0$ (same assumptions for C^f). One can derive aggregate abatement cost functions as follows: Let x_i be the national abatement levels relative to business-as-usual, and let $C_i(x_i)$ be the national abatement cost functions. The aggregate abatement cost function $C(x)$ is defined as
$C(x) = \text{Min}_{xi}\{\sum_i C_i(x_i) | \sum_i x_i = x\}$. This is as if individual payments for mitigation were aggregated into a fund that would reduce emissions where it is the cheapest to do so. Baseline emissions and abatement costs in region i are independent from abatement in other regions. Thus, there are no leakage across regions in our model (see Burniaux and Oliveira Martins 2010, for a discussion of this issue).

[16] To ensure the existence of a solution, we also need that damages be reducible to zero if mitigation expenditures are high enough. Technically, let $\bar{x}$ be the level of abatement achieved if all available resources (short of maximum damages) were allocated to mitigation, i.e., $\bar{x} = C^{-1}(\sum_i l_i y_i) + C^{f-1}(\sum_i l_i^f (a_i^f - d_i(0)))$. We assume that for all $x \geq \bar{x}$ and all regions, $d_i(x) = 0$.

[17] Guesnerie (2004), Heal (2007) and Sterner and Persson (2008) show the importance of including a preference for the environment as an argument of the utility function to carry out a cost–benefit analysis of climate policies. In our model this inclusion is made indirectly by subtracting damages from total households' consumption.

[18] U_i and U_i^f are twice differentiable in all variables, with $U_i' > 0$, $U_i'' < 0$, and $\frac{\partial U_i^f}{\partial d_j} < 0$.

are defined by

$$\alpha_i = \frac{\alpha}{U_i'(y_i)} \tag{7}$$

With

$$\alpha = \left(\sum_i \frac{l_i}{U_i'(y_i)}\right)^{-1} \qquad \text{so that} \sum_i \alpha_i = 1 \tag{8}$$

Second, *attitudes towards the future distribution of income* can be captured via weights attached to individual utility functions at second period. Measuring relative income across countries is not easy, but Negishi weights α_i can be reasonably derived from observable data at first period. This is not the case at second period. In addition to the intrinsic uncertainty surrounding countries' growth rates, there is political uncertainty about which balancing will prevail amongst two polar alternatives:

- Weights based on first-period incomes: This option translates a configuration in which developed countries succeed in imposing on the benevolent planner that the balance of power stemming from the current distribution of income be protected over time. In this *status quo* mandate (hereafter S), the second-period component of W is $\sum_i \alpha_i l_i^f U_i^f$, where α_i are the *first-period* Negishi weights.
- Weights aligned on expected second-period incomes: In this option, developed countries are not influential enough to impose a status quo mandate on the planner or accept that developing countries will eventually catch up. But they still veto deals that would result in any wealth transfer *relative to* the future distribution of income resulting from the catch-up process (Eq. 6). In this *catch-up* mandate (hereafter C), the second-period component of W is $\sum_i \beta_i l_i^f U_i^f$, where β_i are the Negishi weights associated with the expected distribution of income at second period y_i^f:[19,20]

$$\beta_i = \frac{\beta}{U_i^{f\prime}(y_i^f)} \tag{9}$$

with

$$\beta = \left(\sum_i \frac{l_i^f}{U_i^{f\prime}(y_i^f)}\right)^{-1} \qquad \text{so that} \sum_i \beta_i = 1 \tag{10}$$

[19] We assume here that there is common agreement about the future distribution of income.

[20] Negishi weights β_i could be calibrated on net per capita income at second period $y_i^f - d_i$, i.e., after accounting for the impacts of climate change. We do not retain this option to clearly distinguish between uncertainty about economic growth in the absence of climate change and uncertainty about climate change damages.

Table 1 Intertemporal welfare functions in the four planner's mandates

	Catch-up (C)	Status quo (S)
Dynastic (D)	$W_{CD} = \sum_i \alpha_i l_i U_i(c_i) + \varphi \sum_i \beta_i l_i^f U_i^f(c_i^f)$	$W_{SD} = \sum_i \alpha_i l_i U_i(c_i) + \varphi \sum_i \alpha_i l_i^f U_i^f(c_i^f)$
Universal (U)	$W_{CU} = \sum_i \alpha_i l_i U_i(c_i) + \varphi \sum_i \beta_i l_i^f U_i^f(c_i^f, d_{j\neq i})$	$W_{SU} = \sum_i \alpha_i l_i U_i(c_i) + \varphi \sum_i \alpha_i l_i^f U_i^f(c_i^f, d_{j\neq i})$

Third, *attitudes towards damages falling on other countries* can be translated in the arguments of the utility functions. Assuming that parties share common beliefs about regional damages (Eq. 2), a 'dynastic solidarity' ethics (hereafter D) will lead parties to include only their own descendant's consumption into the utility functions U_i^f and make it dependent upon domestic damages d_i only (via the budget Eq. 2). In a 'universal solidarity' ethics (hereafter U), on the other hand, parties will include part of the damages falling on others into U_i^f:[21] U_i^f will be a function of both domestic *and* foreign damages d_i and d_j.[22]

This leads to four logical combinations: catch-up dynastic (CD), status quo dynastic (SD), catch-up universal (CU), and status quo universal (SU). With φ a pure time preference common to all parties the four mandates finally write as indicated in Table 1.

In this model, climate negotiations boil down to a one-shot decision in which abatement expenditures at first and second periods are decided simultaneously. This is arguably at odds with the sequential nature of real climate negotiations. However, we retain this "once for all" model for simplicity's sake and because it captures three key features of the real-world negotiation process.[23] First, parties are now discussing medium-term commitments over the next two or three decades, not just commitments over the next 5 years. Second, governments will not sign agreements that have blatantly detrimental implications for their country in the medium and long term. Third, the agreement has to incorporate some rigidity to minimize strategic games between negotiation periods and to preserve the dynamic efficiency of the regime. For example, changing rules too drastically or too often in a carbon trading system makes it difficult for agents to form expectations and might lead them to refrain from trading (OECD 1993).

[21] Future utility functions are unobservable. We take the position that functions U_i^f represent Parties' views about their descendents' utilities.

[22] An alternative framework is possible under the ethical condition that individual agents have sustainable preferences taking into account long-term future as well. Chichilnisky (2010) demonstrates that under limited arbitrage, such preferences then lead to a sustainable market equilibrium.

[23] Because the main focus of our paper is on the relationships between *inter* and *intra* generational distributions, we adopt a two-period model (as opposed to a model with an infinite number of periods), which leaves aside critical discussions about how to include long-term sustainability concerns within intergenerational social welfare functions. The latter debate is addressed in this issue by Asheim et al. (2010), Figuières and Tidball (2010), and Lauwers (2010).

3 Burden sharing at first period: a simple rule of thumb?

At first period, all programs yield the same solution (Appendix A): abatement expenditures should be allocated so as to equate weighted marginal utilities of consumption (WMUs). This comes back to the seminal result of Chichilnisky (1993), developed by Chichilnisky and Heal (1994) and Chichilnisky et al. (2000), and more recently in Sheeran (2006). This is, *mutatis mutandis*, the BLS condition for the provision of a public good.

$$\alpha_1 U_1'(y_1 - a_1) = \cdots = \alpha_N U_N'(y_N - a_N) \tag{11}$$

Since *before-abatement* WMUs are equal by virtue of the Negishi weights, the optimal distribution of abatement costs is such that WMUs are decreased by the same amount:

$$\alpha_1 U_1'(y_1) - \alpha_1 U_1'(y_1 - a_1) = \cdots = \alpha_N U_N'(y_N) - \alpha_N U_N'(y_N - a_N) \tag{12}$$

Assuming contributions a_i remain small relative to initial revenues,[24] Eq. (12) can be approximated by:

$$-\frac{U_1''}{U_1'}(y_1)a_1 = \cdots = -\frac{U_N''}{U_N'}(y_N)a_N \tag{13}$$

For utility functions with decreasing absolute risk aversion, the optimal a_i are thus increasing with income. They are strictly proportional to it for logarithmic functions.

$$\frac{a_1}{y_1} = \cdots = \frac{a_N}{y_N} \tag{14}$$

Thus, in all mandates, the optimal distribution of abatement expenditures at first period can be encapsulated in a simple rule of thumb, i.e., mitigation costs in proportion of per capita income. This rule can be viewed as a politically astute translation of the common but differentiated responsibilities principle of the UNFCCC.[25,26]

It provides a basis for differentiating coordinated domestic carbon taxes (Cooper 2000) or for compensating for the uneven income effects of a unique carbon price

[24] Contributions a_i can be considered 'small' in mathematical terms if they are less than 5% of y_i—which corresponds to an extraordinary large mitigation effort.

[25] With a logarithmic utility function, each European should contribute 15–76 times as much as the average Indian depending on the whether purchasing power parities or current exchange rates parities are used to compare real income levels (2000 Gross National Income, World Bank 2004).

[26] For diplomatic reasons (see the last-minute statement by the G77 and China mentioned in the introduction), negotiators going to Kyoto had accepted the idea that only developed countries would take commitments. As a result, the Kyoto Protocol follows the UNFCCC (see Footnote 2) and only embodies a very crude differentiation, i.e., efforts in the North, none in the South, leading to an implicit price of carbon of zero for developing countries, and the critical issue of differentiation remains unaddressed (Chichilnisky 2010).

set by a cap-and-trade regime.[27] Moreover, difficulties in comparing real incomes notwithstanding, this rule can be computed through observable parameters and independently of the optimal level of public goods $x + x^f$. But this rule does not lead to disconnecting negotiations on burden sharing from setting climate objectives. As we will see later indeed, the optimal level of mitigation at first period depends on the distribution of income at second period, which in turns determines the aggregate value of the future distribution of mitigation and damages.

4 Second period: troubling consequences of ethical attitudes

At second period, the equalization of WMUs after abatement now applies to the *total* climate change bill, i.e., abatement expenditures *plus* residual damages, and it yields unexpected results. We first analyze the dynastic mandates, starting with the CD variant. Then we examine the extent to which universal solidarity mandates (CU and SU) overcome the problems identified with the dynastic mandates.

4.1 Catch-up dynastic mandate: the winners-losers dilemma

In a CD mandate, the key result is that the equalization of after-abatement WMUs may not be possible under the constraint of non-negative abatement expenditures (Eq. 6).

Let ψ_i be the set of shadow prices associated with inequalities (6) in each region. The general second-period equilibrium can be written as in (15) and (16) below (see Appendix A). If all ψ_i are zero, then all second-period abatement expenditures are non-negative (all countries abate). But if one of them is positive, then that particular country does not abate. The constraint is binding and, in this corner solution, WMUs are not equated.

$$\beta_1 U_1^{f\prime}\left(y_1^f - d_1(x+x^f) - a_1^f\right) \\ -\psi_1 = \cdots = \beta_N U_N^{f\prime}\left(y_N^f - d_N(x+x^f) - a_N^f\right) - \psi_N \tag{15}$$

with

$$\begin{cases} \psi_i = 0 & \text{if } a_i^f > 0 \\ \psi_i > 0 & \text{if } a_i^f = 0 \end{cases} \tag{16}$$

A positive shadow price ψ_i characterizes countries that suffer from damages so high that, even without contributing to mitigation at all, they face higher welfare losses than the others.

[27] In a cap-and-trade regime, the planner can use the initial allocation of emission quotas to offset the welfare losses that might result from a uniform price of emissions allowances. In a tax system, a distinction has to be made between the industrial sector, where taxes must be equated to avoid distorting international competition, and the domestic sector, where taxes can be differentiated (Hourcade and Gilotte 2000). On the price versus quantity debate, see also in this issue (Karp and Zhang 2010).

Table 2 Optimal mitigation policy at second-period (abatement expenditures, residual damages and total climate bill): catch-up dynastic mandate

	Distribution of damages		Optimal mitigation policy					
	Maximum damage N (w/o mitigation) (%)	Maximum damage S (w/o mitigation) (%)	Abatement expenditures N (a_N^f) (%)	Residual damages N (d_N) (%)	Total climate bill N ($a_N^f + d_N$) (%)	Abatement expenditures S (a_S^f) (%)	Residual damages S (d_S) (%)	Total climate bill S ($a_S^f + d_S$) (%)
a	3	3	0.60	1.09	1.69	0.60	1.09	1.69
b	2.59	4	0.75	0.94	1.69	0.24	1.45	1.69
c	2.17	5	0.84	0.79	1.64	0.00	1.81	1.81
d	1.76	6	0.85	0.64	1.49	0.00	2.17	2.17
e	1.34	7	0.86	0.48	1.34	0.00	2.53	2.53
f	0.93	8	0.86	0.33	1.19	0.00	2.88	2.88
g	0.52	9	0.87	0.19	1.06	0.00	3.22	3.22
h	0.10	10	0.88	0.04	0.92	0.00	3.57	3.57

All figures are a percentage of second-period income per capita
Source: Authors' calculation. See Appendix B for calibration details

To show the plausibility of this configuration, let us consider two regions, North (N) and South (S), with identical (logarithmic) utility functions, but with per capita income in N 23 times higher than in S at first period.[28] Let us also assume that a higher per capita income growth in S (3% per year vs. 2.5%) reduces this gap to 18 times in 2050—the beginning of the second period. We posit one aggregate damage function for the world (see calibration in Appendix B) and compute the optimal abatement expenditures, the optimal residual damages, and the optimal total climate change bills according to (15) and (16) for various *distributions* of those aggregate damages between S and N (Table 2).

The optimal distribution of abatement expenditures remains proportional to per capita income if and only if damages per capita represent the same proportion of income in N and S (scenario a in Table 2). If, as suggested by IPCC (2007), damages rip off a higher share of income in S than in N, the representative individual of N will devote a higher share of its income to abatement so that the total climate bills still represent the same proportion of the revenues in both regions. In scenario b (Table 2), for climate change bills representing the same share of incomes of N and S (1.69%), N spends 0.75% of its second-period revenue for mitigation, against 0.24% for S.

But when damages become very large in S relative to N (in scenario c, for example) S faces a higher climate bill than N (1.81 vs. 1.64%) even with zero abatement expenditures. This corner solution is far from implausible for Africa, small Island-States, Central America or Bangladesh, and it puts the no-redistribution constraint to a serious test since, to equate the WMUs, one would need to compensate these countries for the 'excess' damages they withstand through negative abatement expenditures

[28] Twenty-three is the 2002 gap in per capita gross national income between high-income countries, and low- and middle-income countries (World Bank 2004).

(i.e., direct or indirect transfers). In fact, this calls for a more lenient interpretation of the no-redistribution constraint, which applies to the *sum* of damages and abatement expenditures:

$$a_i^f + d_i \geq 0 \tag{17}$$

This alternative formulation would lead to higher aggregate welfare, but it contradicts the dynastic solidarity rationale. It would imply that countries likely to benefit from or not to be affected much by global warming would commit themselves to compensating countries that are severely hurt. Moreover, the amount of these compensations is almost unpredictable given the level of uncertainty surrounding climate projections at regional level (IPCC 2007).[29] Historically, uncertainties about mitigation costs have led many countries to hesitate before accepting the Kyoto Protocol (Hourcade and Ghersi 2002) and have even led some to walk away entirely. And yet, countries have some control over abatement costs, while they have basically no control over impacts. It is thus unlikely that countries will accept the risk of paying significant compensations for 'excess' damages without changing their overall attitude towards climate risks—which will be envisaged in the universal solidarity mandates.

4.2 Status quo dynastic: a paradoxical but meaningful outcome

This SD mandate faces the same problem of uneven geographical distribution of damages than the CD mandate, but, in addition, because the weights attached to individual utility functions are the Negishi weights of the *first-period* income levels, it leads to a paradoxical outcome.

The first-order condition is given in Eq. (18) below.

$$\begin{aligned} &\alpha_1 U_1^{f\prime}\left(y_1^f - d_1(x + x^f) - a_1^f\right) \\ &\quad -\psi_1 = \cdots = \alpha_N U_N^{f\prime}\left(y_N^f - d_N(x + x^f) - a_N^f\right) - \psi_N \end{aligned} \tag{18}$$

Since the weights α_i are constructed so that the distribution of *first-period* income is welfare maximizing, the vector of *second-period* income y_i^f has no reason to be welfare maximizing. In most instances, in fact, it is not, and before abatement WMUs are different. It is then optimal to charge all abatement expenditures to the country with the lowest WMU, so as to decrease its income and increase its WMU. The planner shall do so until both WMUs are equal (Fig. 1).

This paradox occurs with fairly conservative assumptions about growth rates. Let us assume that the developing world grows by 3% annually over the next decade from

[29] Projections of future world average temperatures by global circulation models have a far higher degree of confidence than projections at local scale. And uncertainty grows by another order of magnitude when local physical impacts are translated into economic damages: Western Europe may experience either warming by 2°C or more or cooling by several degrees depending on the evolution of the North-Atlantic thermohaline circulation. Russia is often regarded as a potential winner of global warming. But the melting of the permafrost, or dryness in the South of the country might put it among the losers.

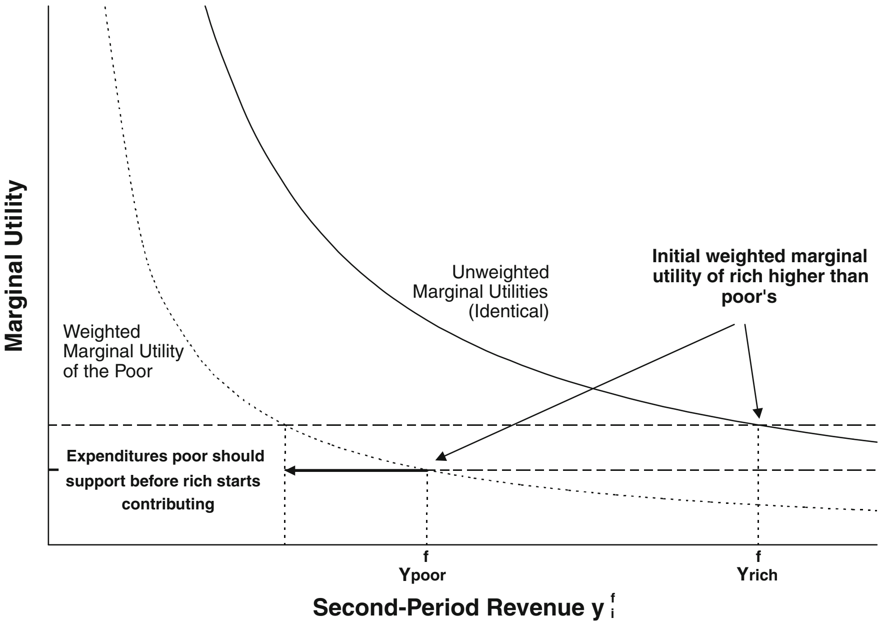

Fig. 1 Optimal abatement levels at second-period for two regions differing only by income in SD mandates

now on, while rich countries grow by only 2.5%. Then the developing world is about 5% richer in 2019 than it would have been with a 2.5% growth rate. This 'extra' growth amounts to about 1% of the world GDP in 2019, and a planner following the SD mandate would allocate all the mitigation costs on the developing world, as long they do not exceed one percent of the World GDP in 2019.

This paradox is unlikely to disappear when accounting for the damages of climate change. For example, with a per capita growth in the developing world again half a point higher than in developed countries over the next 50 years, per capita GDP in 2059 is 27% higher in the developing world than it would have been had both rates been equal. Regional damages apt to outweigh this 'extra-growth' go beyond the most pessimistic climate change scenarios.

This paradox is obviously a theoretical artifact due to the one-shot character of the model. But it helps demonstrating the consequences of ethical attitude behind the status-quo mandate, i.e., the extension of the grandfathering principle to future generations. In Eq. (18) the future inhabitants of the rich countries are de facto endowed with emissions rights based on those of their predecessors—an allocation of rights consistent with the claim by some countries that "lifestyles are not negotiable."[30] This deal is obviously not acceptable for developing countries given that it is so blatantly detrimental to them, and given the uncertainty and political costs of reversing any diplomatic *fait accompli.*

[30] This warning, often attributed to George H. Bush Sr., would probably be endorsed, albeit in more diplomatic terms, in many quarters of the developed world.

The above analysis thus shows that the deals resulting from mandates supported by a dynastic solidarity ethics run a risk of rejection or, if accepted, of dynamic instability as some parties will have strong incentives to defect or to try and prevent entry into force. The CD mandate confronts the reluctance of countries to commit themselves ex ante to compensating for unpredictable damages falling on other countries ex post. In addition, the SD variant is unacceptable by poor countries because it leads to a second-period equilibrium where they are asked to support most of the mitigation effort.[31]

4.3 Universal solidarity: a prerequisite but no way out?

The fact that dynastic solidarity translates the behavior of "cold monster States" does not imply that, symmetrically, universal solidarity can derive only from a utopian *universal bonhomie*, or from Schelling's thesis (1995) that, beyond some horizon, all future individuals are indistinguishable. In fact, a universal solidarity ethics can be based on pure self-interest as well. Faced with uncertainties regarding the location of damages, parties might refrain from indulging themselves among the 'winners' of global warming.[32] Similarly, the risks of global spillovers from local shocks (including accelerated migrations) may lead parties to consider that any damage of climate change anywhere in the world will ultimately affect everyone's welfare and security. This is basically the key message of Stern (2007). In the strict etymological meaning of the term, one can show solidarity with somebody either for reasons of benevolence or because our interests stick together. In this light, even a SU mandate is plausible if it is interpreted as translating a clear selfish attitude: conserving the current balance of powers, but taking possible negative spillovers into account.

4.3.1 A burden-sharing more robust to uncertainty?

In U mandates, both domestic and foreign damages enter into the utility functions, and this automatically makes the allocation of abatement expenditures less sensitive to the geographical distribution of damages. The question is whether that effect is sufficient to palliate the limitations of the dynastic mandates.

In the SU mandate the optimal distribution of abatement expenditures is governed by Eq. (19)[33] below, where the shadow prices associated with constraint (6) are again governed by Eq. (16).

[31] It is precisely the lack of clarification that future quotas would not be allocated through grandfathering that led the G77 to veto the rules governing carbon trading in the penultimate day of the Kyoto Conference.

[32] A situation analogous to the "veil of ignorance" of Rawls (1971).

[33] The self-interest justifications for the universal mandate imposes that $\frac{\partial^2 U_i^f}{\partial c \partial d_j} \neq 0$, so that damages abroad impact on marginal utilities of consumption (directly or through compensation or security expenditures) and not only on utility levels.

Table 3 Optimal mitigation policy at second-period (abatement expenditures, residual damages and total climate bill): catch-up universal mandate

Scenario		Optimal mitigation policy					
Damage maximum North (%)	Damage maximum South (%)	Abatement expenditures N (a_N) (%)	Residual damages N (d_N) (%)	Total climate bill N ($a_N + d_N$) (%)	Abatement expenditures S (a_S) (%)	Residual damages S (d_S) (%)	Total climate bill S ($a_S + d_S$) (%)
a 3	3	1.28	0.59	1.87	1.28	0.59	1.87
b 2.59	4	1.36	0.51	1.87	1.09	0.78	1.87
c 2.17	5	1.44	0.43	1.87	0.89	0.98	1.87
d 1.76	6	1.52	0.35	1.87	0.69	1.18	1.87
e 1.34	7	1.61	0.26	1.87	0.49	1.38	1.87
f 0.93	8	1.69	0.18	1.87	0.30	1.57	1.87
g 0.52	9	1.77	0.10	1.87	0.10	1.77	1.87
h 0.10	10	1.81	0.02	1.83	0.00	1.96	1.96

All figures are a percentage of second-period income per capita
Source: Authors' calculation. See Appendix B for calibration details

$$\alpha_1 U_1^{f\prime}\left(y_1^f - d_1(x+x^f) - a_1^f, d_2, \cdots, d_N\right) - \psi_1 \\ = \cdots = \alpha_N U_N^{f\prime}\left(y_N^f - d_N(x+x^f) - a_N^f, d_1, \ldots, d_{N-1}\right) - \psi_N \qquad (19)$$

The same set of equations is valid for the CU mandate, with the only difference that coefficients β_i replace coefficients α_i:

$$\beta_1 U_1^{f\prime}\left(y_1^f - d_1(x+x^f) - a_1^f, d_2, \ldots, d_N\right) - \psi_1 \\ = \cdots = \beta_N U_N^{f\prime}\left(y_N^f - d_N(x+x^f) - a_N^f, d_1, \ldots, d_{N-1}\right) - \psi_N \qquad (20)$$

The comparison between U mandates and their D cousins depends on whether a universal solidarity ethics changes the perceived aggregate damages. Recognizing the existence of propagation effects across countries is consistent with the idea of a cost-multiplying effect associated with this propagation (Hallegatte et al. 2007). However, we will reason at constant aggregate damages in order to avoid controversies about the magnitude of this multiplying effect and will focus on the sole impact of changing the weights in the social welfare function. Under this assumption, what we know of the magnitude of damages is again too low to correct the likely differences in WMUs before abatement in the status-quo version of the U mandate. The SU mandate is thus likely to face the same paradox as its SD cousin. Conversely, because before-abatement WMUs are equal at second period in catch-up mandates, their universal solidarity version may overcome the deadlocks of their dynastic version, provided the weight of other countries in one's utility function is large enough. This can be illustrated through a simple numerical example with the same regions and assumptions as in Sect. 4.2 (see Appendix B). Second-period utility functions now depend both on domestic consumption and on aggregate damages (21), with d_i^{max} the damages falling on region i if there were no abatement.

$$U = \ln(c)\left(1 - 0.01\frac{d_S + d_N}{d_S^{\max} + d_N^{\max}}\right) \tag{21}$$

Keeping aggregate damages constant, we compute the optimal mix of abatement expenditures and residual damages under several assumptions about the distribution of these damages between S and N. In Table 3, we see that a corner solution is obtained only for very uneven distribution of damages (maximum damages of 10% in S against 0.1% in N) in the CU mandate, whereas this corner solution is reached more easily in the CD mandate (maximum damages of 5% in S against 2.2% in N).

That a universal solidarity ethics enhances the chances of following a BLS-like rule at both periods in case of catch-up mandate reinforces its acceptability at first period. Its very logic indeed minimizes the consequences of mispredictions in terms of dynamic consistency of the initial agreement since part of the perceived damages is independent from where damages fall.

4.3.2 A higher provision of global public good

In addition to easing the tensions over burden sharing, the CU mandate results into a higher optimal level of abatement. The planner will indeed have to consider a higher total value of damages, even without considering that the propagation effects will increase the total level of impacts, for the reason that the rich low-impacted countries will take into account part of the damages that fall on poor countries.

To see the difference between the U and D mandates in terms of provision of global public goods, let us come back to the CD mandate and assume an interior solution. The optimal abatement levels are given by Eqs. (23) and (22) below, where ρ is the average consumption discount factor deriving from the utility discount factor φ, the economic growth rate, and the shape of the utility functions (see Appendix A for a detailed expression of ρ).

$$C^{f\prime}(x^f) = -\sum_i l_i^f d_i'(x + x^f) \tag{22}$$

$$C'(x) = \rho C^{f\prime}(x^f) \tag{23}$$

This is the standard result that the climate should be protected up to the point where the marginal costs of mitigation equal the discounted sum of the marginal benefits in terms of avoided damages. The aggregate marginal damage function $-\sum_i l_i^f d_i'$ is the only determinant of the level of abatement, and the weights α_i and β_i do not play any role.[34] This allows for two types of separability: separability between the level of action and the distribution of abatement expenditures across countries, and separability between the level of action and the distribution of climate change impacts across countries.[35]

But this separability is lost in a CU mandate in which, again assuming an interior solution, the optimal level of abatement is given by Eqs. 24 and 25 below (see Appendix A for general forms). The additional term in the right-hand side of Eq. 24 translates the fact that country i takes into account damages falling on other countries as well as damages falling on its own citizens. Since marginal damages and partial derivatives of utility relative to damages are both negative, their product is positive. Marginal abatement costs are thus higher than they would be in the CD mandate, leading to a higher level of abatement at optimum. The extent to which abatement is higher is no longer independent from the distribution of income at second period.

$$C^{f'}(x^f) = \sum_i l_i^f \left[-d_i'(x + x^f) + \rho \sum_{j \neq i} \frac{\frac{\partial U_i^f}{\partial d_j}}{U_i^{f'}} d_j'(x + x^f) \right] \tag{24}$$

$$C'(x) = \rho C^{f'}(x^f) \tag{25}$$

For example, assuming equal damages per capita in S and N (scenario a in Table 2), the optimal level of abatement at second period is 29% below baseline in the CD case. With utility functions of the form 21), the optimal level of abatement is 41% in the CU case (scenario a in Table 3)—a considerable 44% increase. A non-negligible side-effect of higher levels of abatement overall is that damages in S never exceed 2% of income, while they can reach 3.6% in the CD case.

5 Conclusion

Although greatly influenced by political vagaries, the language of climate negotiations remains framed by an economic wisdom in which (a) the optimal level of mitigation results from priors about climate change damages and from the value of the pure time preference, (b) intragenerational equity can be secured, for whatever mitigation objective, via appropriate transfers, and (c) it is neither legitimate nor realistic to transform climate policies into a tool for large-scale international redistribution of wealth.

This paper suggests that this framing misses two dimensions that prove critical when the climate affair is examined from a dynamic perspective. The first dimension is whether negotiations are conducted in function of the *current or future distribution*

[34] The reason is that the marginal utility of consumption of the public good is the marginal utility of consumption times the avoided damage. Since the Negishi weights are proportional to the inverse of the marginal utility of consumption, they cancel out, and only the sum of avoided damages remains.

[35] If the equilibrium is a corner solution, the optimal level of abatement *increases* relative to the interior solutions because some countries have a higher WMU than the others. In Table 1, for example, the optimal abatement level in scenario h—in which all damages fall on S —is 1.4% higher than in scenario a where N and S are equally impacted.

of economic wealth. The second is *whether individuals show solidarity to their own descendants only or to all the future human beings*.

The first implication of capturing these two dimensions is theoretical. The weights attached to individual utility functions define the baseline from which the no-redistribution constraint applies and affect the aggregate discounted value of future consumption and the optimal level of mitigation. Thus, (a) the pure time preference (Stern 2007; Nordhaus and Yang 2007; Heal 2007; Sterner and Persson 2008; Hourcade et al. 2009) is no longer the sole determinant of the trade-off between present and future aggregate consumption, and (b) intra- and intergenerational equity cannot be treated separately, since assumptions about future income distribution and about the scope of intergenerational solidarity impact on the value of future damages and on the optimal provisions of abatement.

The second implication concerns the conditions for a viable international climate architecture. Of the four mandates combining *status quo* or *catch-up* attitudes towards future distribution and income, and *dynastic* or *universal* solidarity towards future individuals, we show that three are dynamically inconsistent and thus self-defeating. They either result in putting the entire burden on developing countries (status quo/dynastic and status quo/universal) or prove difficult to reach because of the uncertainty about the location of damages (catch-up dynastic).

The *catch-up universal* mandate yields a stable outcome because it recognizes potential changes in world income distribution and reduces the role of uncertainty in the geographical location of impacts and in their transboundary propagation. It has two main characteristics: first, a higher optimal level of public goods relative to the others;[36] second, an optimal allocation of mitigation expenditures at first period in general proportional to per capita income[37]—which might be a good translation of the "common but differentiated responsibilities" principle of the UNFCCC.

Although we have stuck here to the dominant view that mitigation constitutes a net burden at first period, our intuition is that these insights hold even in the perspective of Pareto-improving policies.[38] The political will of paying the transaction costs of deploying these policies is not unrelated to attitudes regarding solidarity in the face of climate damages or regarding the evolving discrepancies in development levels. Ultimately, the point is that negotiating the allocation of a global cap in GHGs emissions as a pure 'carbon price plus transfers' exercise, in isolation of broader issues such as the rebalancing of economic power across countries over the coming decades or the enhancement of global security, may lead to a systematic impasse as just demonstrated

[36] Even though in a static one-period framework, a stronger preference for equity may lead to less action on climate change because low-income populations have a lower marginal utility of the environment, here, whatever the selfish or altruistic character of its motivation, a universal solidarity attitude that includes concerns about the situation of poor populations enhances the need for action.

[37] For logarithmic or power utility functions. With more general utility functions, optimal efforts are typically increasing with income.

[38] To identify margins of freedom for strategies with no consumption loss for the current generations of rich countries and no slowdown in the take off of developing countries, one needs a multi-goods model to study how investments can be massively redirected (200–400 G$ in 2030 according to World Bank 2009) and how those that lose from this redirection may be compensated. Using a game-theory approach, Dutta and Radner (2010) provide general conditions on how such transfers could be effective.

in Copenhagen. It is critical indeed to reflect upon the conditions under which a *status-quo universal* mandate can be adopted. We hope that further developments of the theoretical line just opened in this paper will be fruitful to scrutinize in depth these conditions and how they might open a negotiation space more conducive to a positive outcome.

Appendix A: Model resolution

We solve a general version of the planner's problem (a1)—in which coefficients χ_i summarize both S and C mandates (a2)—under constraints (3), (4), (5), and (6).

$$\text{Max}_{\{a_i, a_i^f\}} \sum_i \alpha_i l_i U_i(y_i - a_i) + \varphi \sum_i \chi_i l_i^f U_i^f \left(y_i^f - a_i^f - d_i(x + x^f), d_{j \neq i} \right) \tag{a1}$$

With

$$\chi_i = \begin{cases} \alpha_i = \frac{\alpha}{U_i'(y_i)} \text{ in S mandates, with } \alpha = \left(\sum_i \frac{l_i}{U_i'(y_i)} \right)^{-1} \\ \beta_i = \frac{\beta}{U_i'(y_i)} \text{ in C mandates, with } \beta = \left(\sum_i \frac{l_i^f}{U_i^{f'}(y_i^f)} \right)^{-1} \end{cases} \tag{a2}$$

Let λ, $\varphi\,\mu$, $l_i \xi_i$, and $\varphi l_i^f \psi_i$ be the Lagrange multipliers attached to constraints (3), (4), (5), and (6) respectively. Since (5) and (6) are inequality conditions, ξ_i and ψ_i are such that

$$\begin{cases} \xi_i = 0 & \text{if } a_i > 0 \\ \xi_i > 0 & \text{if } a_i = 0 \end{cases} \tag{a3}$$

$$\begin{cases} \psi_i = 0 & \text{if } a_i^f > 0 \\ \psi_i > 0 & \text{if } a_i^f = 0 \end{cases} \tag{a4}$$

With these notations, the Lagrangean of the problem becomes

$$\begin{aligned} L = & \sum_i \alpha_i l_i U_i(y_i - a_i) + \varphi \sum_i \chi_i l_i^f U_i^f \left(y_i^f - a_i^f - d_i(x + x^f), d_{j \neq i} \right) \\ & + \lambda \left[\sum_i l_i a_i - C(x) \right] + \varphi\mu \left[\sum_i l_i^f a_i^f - C^f(x^f) \right] + \sum_i l_i \xi_i a_i + \varphi \sum_i l_i^f \psi_i a_i^f \end{aligned} \tag{a5}$$

The first-order condition with regard to a_i is

$$\frac{\partial L}{\partial a_i} = 0 \Rightarrow \alpha_i U_i'(y_i - a_i) - \xi_i = \lambda \tag{a6}$$

We first demonstrate that (a6) has a unique solution with strictly positive abatement levels a_i. Let us assume without loss of generality that a_1 were zero. Since $\xi_1 > 0$, $\alpha_1 U_1'(y_1 - a_1) - \xi_1 = \alpha_1 U_1'(y_1) - \xi_1 < \alpha_1 U_1'(y_1)$. If another abatement level, say a_2, were strictly positive, then $\alpha_2 U_2'(y_2 - a_2) - \xi_2 = \alpha_2 U_2'(y_2 - a_2) > \alpha_2 U_2'(y_2)$ since marginal utilities are strictly decreasing functions. Yet by definition of the Negishi weights, $\alpha_1 U_1'(y_1) = \alpha_2 U_2'(y_2)$. Thus, we would have $\alpha_1 U_1'(y_1 - a_1) - \xi_1 < \alpha_2 U_2'(y_2 - a_2) - \xi_2$, contradicting Eq. (a6). Thus, if one of the abatement expenditures is zero, all abatement expenditures are zero.

But if all a_i were zero, Eq. (3) and the fact that $C(0) = 0$ would imply that $x = 0$, and thus that marginal costs of abatement C' are zero. Equalization between marginal costs of abatement and marginal damages at optimum (Eq. a11) would then imply that all marginal damages $d_i'(x + x^f)$ be zero, and thus (via Eq. a8) that the marginal costs of mitigation at second period be zero, and thus that the level of abatement at second period $x^f = 0$. But this would contradict the assumption that no abatement leads to strictly positive marginal damages of climate change. First-period abatement levels a_i are thus all strictly positive, and since marginal utility functions are strictly decreasing, they are uniquely defined.

Similarly, derivation of L with regard to a_i^f yields

$$\frac{\partial L}{\partial a_i^f} = 0 \Rightarrow \chi_i U_i^{f'} \left(y_i^f - a_i^f - d_i(x + x^f), d_{j \neq i} \right) - \psi_i = \mu \tag{a7}$$

The second part of the argument above can be replicated to demonstrate that at least one of the second-period abatement expenditures a_i^f is strictly positive. But the first part of the argument above cannot be applied as is, and thus there is no guarantee that *all* second-period abatement expenditures be strictly positive.

In C mandates, this is because marginal utilities before abatement *and after damages* $\chi_i U_i^{f'}(y_i^f - d_i(x + x^f))$ have no reason *a priori* to be equal. We only know that marginal utilities of consumption before abatement *and before damages* $\chi_i U_i^{f'}(y_i^f)$ are equal (by construction), and thus that the *aggregate climate bills* $a_i^f + d_i$ (and not just the abatement expenditures component) are all strictly positive.

In S mandates, even that weaker property does not hold because even marginal utilities of consumption before abatement and before damages $\chi_i U_i^{f'}(y_i^f)$ have no reason a priori to be equal across regions.

Derivation of L with regard to x^f yields

$$C^{f'}(x^f) = \sum_i l_i^f \pi_i \left[-d_i'(x + x^f) + \rho \sum_{j \neq i} \frac{\frac{\partial U_i^f}{\partial d_j}}{U_i^{f'}} d_j'(x + x^f) \right] \tag{a8}$$

with

$$\pi_i = \frac{\chi_i}{\mu} U_i^{f'} \left(y_i^f - d_i(x + x^f) - a_i^f, d_{j \neq i} \right) = \frac{\chi_i U_i^{f'}}{\chi_i U_i^{f'} - \psi_i} \tag{a9}$$

Given the assumptions made about marginal damages and marginal abatement costs, (a8) has a unique solution. Coefficients π_i are the ratios of $\chi_i U_i^{f\prime}$ the weighted marginal utility of consumption of country i, and of μ the weighted marginal utility of consumption *of the countries that abate at second period* (as per Eq. a7) (μ can also be interpreted as the shadow price of abatement at second period, expressed in marginal utility terms). When country i contributes to abatement at second period, these two terms are equal and $\pi_i = 1$. When country i does not contribute to abatement—either because it does not grow rapidly enough, or because domestic damages are too high—$\pi_i > 1$.

In other words, when a country has a weighted marginal utility of consumption that is too high relative to the others, not only will it not contribute to abatement, but damages falling on this country will be weighted higher than damages falling on others because they cause higher utility losses at the margin.

When all countries contribute—which, as discussed above, occurs mostly in the C mandates—(a9) simplifies in (a10), which is the standard BLS condition.

$$C^{f\prime}(x^f) = -\sum_i l_i^f d_i'(x + x^f) \tag{a10}$$

Finally, derivation of L with regard to x yields

$$C'(x) = \varphi \sum_i l_i^f \omega_i \left[-d_i'(x + x^f) + \rho \sum_{j \neq i} \frac{\frac{\partial U_i^f}{\partial d_j}}{U_i^{f\prime}} d_j'(x + x^f) \right] \tag{a11}$$

with

$$\omega_i = \frac{\chi_i}{\lambda} U_i^{f\prime} = \frac{\chi_i U_i^{f\prime} \left(y_i^f - d_i(x + x^f) - a_i^f, d_{j \neq i} \right)}{\alpha_i U_i'(y_i - a_i)} \tag{a12}$$

Coefficients ω_i capture the change in weighted marginal utility of consumptions between the first and the second periods. Comparing Eqs. (a8) and (a11), the term $\varphi\omega_i$ can be interpreted as the region-specific discount rate that applies to climate change damages. In C mandates, this term becomes

$$\varphi\omega_i = \varphi \frac{\beta}{\alpha} \frac{U_i'(y_i)}{U_i'(y_i - a_i)} \frac{U_i^{f\prime} \left(y_i^f - d_i \left(x + x^f\right) - a_i^f, d_{j \neq i} \right)}{U_i^{f\prime} \left(y_i^f \right)} \tag{a13}$$

When abatement expenditures and damages remain small with regard to income, the last two terms are close to one, and regional discount factors are all equal to $\varphi \frac{\beta}{\alpha}$. Hence coefficient ρ in Eq. (23). For example, with logarithmic utility functions, $\rho = \varphi \frac{\beta}{\alpha} = \varphi \frac{1}{(1+r)^N}$ where r is the aggregate growth rate of the economy over the first period. In D mandates, on the other hand, regional discount rates become

$$\varphi\omega_i = \varphi \frac{U_i^{f'}\left(y_i^f - d_i\left(x + x^f\right) - a_i^f, d_{j\neq i}\right)}{U_i'\left(y_i - a_i\right)} \tag{a14}$$

which vary depending on the regional growth rate between the two periods. For example, with logarithmic utility functions, $\rho_i = \varphi \frac{1}{(1+r_i)^N}$ where r_i are the regional growth rates over the first period.

Appendix B: data and modeling framework of numerical experiments

The world is divided in two regions: "North" (N) comprises high-income countries, as per World Bank 2004 definition, and "South" (S) low- and middle-income countries. The first period is 2000–2049, and the second 2050–2099. Initial income and population data are from World Bank 2004. Average annual economic growth in N is assumed to be 2.5% between 2000 and 2050, against 3% in S. World population is assumed to grow by 2 billions in that period of time, all of them in S (Table 4). For simplicity's sake, we use 2000 (resp. 2050) figures as averages for period 1 (resp. 2).

Without abatement, World CO_2 emissions are assumed to be 513 $GtCO_2$ during the first period, and 688 $GtCO_2$ during the second, as in the IPCC IS92a scenario (IPCC 1994).

Abatement costs at first and second periods are assumed quadratic with respect to total abatement levels. We also assume that mitigating all the emissions in the world economy would cost at the margin \$1,500/tC during the first period, and \$1,000/tC during the second. After easy manipulations, Eqs. (3) and (4) become

$$x = 1482 \times \sqrt{\frac{l_N a_N + l_S a_S}{l_N y_N + l_S y_S}} \tag{a15}$$

$$x^f = 4066 \times \sqrt{\frac{l_N^f a_N^f + l_S^f a_S^f}{l_N^f y_N^f + l_S^f y_S^f}} \tag{a16}$$

Table 4 Key assumptions in numerical example

	First period (2000–2049)		Second period (2050–2099)	
	l_i (billions)	y_i (1995 USD per capita, exchange rates)	l_i^f (billions)	y_i^f (1995 USD per capita, exchange rates)
North	0.95	26,750	0.95	91,943
South	5.11	1,160	7.11	5,085

Source: World Bank 2004, authors' assumptions for 2050 figures

Damages are assumed cubic with total emissions.

$$d_i(x + x^f) = y_i^f \theta_i \left(1 - \frac{x + x^f}{1201}\right)^3 \tag{a17}$$

Coefficients θ_i represent the maximum damage—expressed as a share of per capita GDP—that each region may sustain because of climate change. If there were no mitigation at all, damages would be $d_i = y_i^f \theta_i$. We use several values for coefficients θ_i to represent various assumptions about the distribution of impacts of climate change across regions—keeping the aggregate maximal damage $l_S^f y_S^f \theta_S + l_N^f y_N^f \theta_N$ constant. Finally, all utility functions are assumed logarithmic, and the rate of pure time preference φ is set to 1%.

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