Optimal Global Climate Policy and Regional Carbon Prices

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Introduction

It is often stated that optimal global climate policy requires global harmonization of marginal abatement costs – i.e., a single carbon price throughout the world. Chichilnisky & Heal 1994 have shown quite generally that this is only the case if distributional issues are ignored, or if lump-sum transfers are made between countries. Else, a policy in which different regions face different carbon prices may be superior to one with a single global carbon price from a welfare point of view. Still, most integrated assessment models (IAMs) assume away distributional issues and report a single optimal carbon price.[1] We calculate utilitarian-optimal carbon prices under zero cross-regional lump-sum transfers in the multi-region IAM NICE. The result is optimal global climate policy with different regional carbon prices in which the poorest regions face initially low prices, while the richest regions face very high prices from the outset. This entails significant welfare gains over the standard single price optima commonly reported, which, as we argue briefly in conclusion, can be improved upon still by allowing international trading in the corresponding emissions allocations. If implemented in a way that makes trading competitive, such a scheme would result in a globally harmonized carbon price. Such a result would constitute an efficient use of carbon resources in a way that addresses the distributional issues internal to the climate problem.

NICE is based on William Nordhaus's multi-regional model RICE, but includes representation of sub-regional inequalities based on World Bank income distribution data (World Bank 2014). This allows us to show not only the effect on optimal prices of allowing differential regional prices while otherwise holding fixed the assumptions of RICE, but also the effect of differential pricing on optimal policy given a variety of alternative assumptions about the distribution, within regions, of both mitigation cost and damages by income quintile.[2]

We find that the effect on optimal policy of allowing different regional prices can be large, even for the relatively low value of 1 for the elasticity of marginal utility, the parameter which determines the intensity of concern for inequality in cost-benefit climate models such as NICE.[3] The optimal regional prices span the whole range of prices that are found using globally aggregated models and that are currently debated as optimal global prices. The richest regions have carbon prices greater than those prescribed with low discounting parameters in the Stern review (Stern 2006), and the poorest regions have even lower prices than found optimal by studies with very high discounting parameters (e.g. Nordhaus 2007). This is robust to a large range of combinations in the other relevant parameter values. The welfare gains and change in global mitigation effort from allowing different regional prices depends on model parameters, in particular the two income elasticities which determine how mitigation costs and climate damages are distributed across income groups within regions. For example, for elasticity values in the middle of our reported range we find that the overall mitigation

[1] The most prominent models are DICE/RICE (Nordhaus & Sztorc 2013), FUND (Tol 1996), and PAGE (Hope 2006). These are either globally aggregated models with no regional heterogeneity (as DICE and PAGE) or regional models run with Negishi weights or a constraint requiring all regions to have the same carbon price (as RICE). Exceptions are Anthoff 2009, which uses FUND, computes an optimum with regionally different carbon prices, as well as Hassler & Krusell 2012 who have a modification of RICE in which there is trade in fossil fuels but no other trade, and report that the optimum would only impose carbon taxes on oil producing countries.
[2] NICE does not model health co-benefits of CO_2 mitigation, which, as shown in the contribution by Boyce, would result in higher carbon prices overall.
[3] For greater values of this elasticity, the spread in regional prices becomes greater. The value 1 is at the lower end of the range of primary disagreement over this parameter in the literature.

effort (measured by total global emissions) is comparable in the harmonized and differential price optima, but the welfare gain from allowing poorer regions to mitigate less is still substantial: over a percent of perpetual equally distributed consumption. Regardless of the parameter values, the welfare gain from considering optimal differential prices is *always* positive since the removal of the harmonization constraint cannot result in a welfare loss.

In the discussion section we argue that the differential prices optimum is a natural focal point for climate policy, as it gives proper weight to common but differentiated responsibilities, and provides a reference for judging the relative adequacy of national commitments (NDCs) in the emerging post-Paris 'bottom-up' international climate regime. Because the differential prices optimum can be used to calculate the welfare-optimal shares of emissions, these shares are then a natural welfare-based focal point for judging the adequacy of shares of a given level of global emissions reductions. Once such commitments are established and deemed adequate, international emissions trading can provide further gains still, as in any situation with differential prices the same emissions level can be achieved in a Pareto improving way by allowing a region with a higher price to pay a region with a lower price for a portion in the latter's emission share – e.g. in an emissions trading scheme that allocates permits according to the emission shares in the differential prices optimum.[4] The resulting gain over the standard harmonized price optimum would be twofold: first from allowing different regional levels of mitigation cost burden, and second from the efficiency gain due to trading. The latter is accompanied by some degree of international transfers, but rather than being lump-sum transfers stemming from cosmopolitan redistributive aims they stem from the logic of common but differentiated responsibilities internal to the climate policy challenge.

Modeling: Optimal Climate Policy with Differential Regional Prices in NICE

Very few papers produce an optimal global response with different price paths for different regions– Anthoff 2009 computes optimal differential prices in the FUND model and also provides an overview of the relevant economic theory. Here we compute the utilitarian-optimal carbon prices in the multi-region integrated assessment model NICE and compare the prices and welfare levels to the harmonized-price constrained optimum as well as to the Negishi-weighted and globally aggregated models.[5] NICE is based on William Nordhaus' multi-region model RICE, but includes sub-regional inequalities represented by aggregating World Bank data on the distribution of income within nations to regional income distributions. These regional income distributions are treated as a proxy for the distribution of consumption prior to both mitigation cost and damage from climate change. The post- mitigation cost and damage consumptions then depend on the way in which these two impacts correlate with consumption, as measured by the impact elasticity of consumption.

[4] The result reached after trading will have a single international marginal abatement cost, but it will depend on the initial allocation, and will, in general, not be the same as the harmonized price optimum. In fact, Chichilnisky, Heal, & Starrett 2000 show that for some initial allocations the result of emissions trading may not even be Pareto efficient. Still, such a result would be superior to the harmonized price optimum.

[5] In all our optima we adopt a constraint against direct international transfers, and we specify an exogenous savings rate of 25.8%, which can be interpreted as the optimal savings rate of private savers with a time-separable and discounted objective with a logarithmic utility function (Dennig et al. 2015, Golosov et al. 2014). There are two alternative treatments of savings in the climate-economy modeling literature: one approach assumes that economic agents endogenously look forward to climate damages and policies and optimally adjust their planned savings (a leading example is in Nordhaus's original versions of DICE and RICE), and another that assumes that savings does not so respond to climate policy optimization (leading examples are FUND and PAGE; in a DICE/RICE framework, see Dennig et al. 2015). Although both approaches are defensible, we prefer and use the second approach, because we find it more realistic to assume that society has a fixed appetite for savings that is essentially insensitive to climate change and climate policy decisions.

Following RICE 2010 (Nordhaus 2010), on which NICE is based, and most of the literature, NICE evaluates public policy with a discounted and separable constant elasticity social welfare function. In general we don't use Negishi weights (though we report the Negishi-weighted optimum for comparison to our results),[6] but only population weights:

$$W(c_{ijt}) = \sum_{ijt} \frac{L_{ijt}}{(1+\rho)^t} \frac{c_{ijt}^{1-\eta}}{1-\eta} \quad (1)$$

Here W denotes social welfare, L population, c per capita consumption, ρ the pure rate of time preference, and η the elasticity of marginal utility. The subscripts *i, j,* and *t* are region, quintile, and time indices respectively.

The main equation embodying the economic trade-off in the RICE model, inherited by NICE is:

$$Y_{it} = \left(\frac{1-\Lambda_{it}}{1+D_{it}}\right) Q_{it} \quad (2)$$

Here Y denotes (net) economic output post-mitigation cost and climate damage, Q denotes pre-cost and damage (gross) output, and Λ and D are mitigation cost and damage respectively. Thus, mitigation comes at a cost that subtracts from output, as do climate damages, which increase as temperature rises relative to preindustrial levels. Temperature increase is a function of the stock of emissions in the atmosphere, which can be controlled (at a cost) by past abatement. As RICE is a regional model, each of these variables is specified by region. Gross output Q is a Cobb-Douglass function with exogenous regional and time varying *total factor productivity*, which is computed as a residual for 2005 and projected forward with empirical growth estimates as well as a modest convergence assumption. The regional damage functions $D_i(T_t)$ are quadratic functions of global mean temperature above pre-industrial levels with coefficients that vary by region. The abatement cost $\Lambda_i(\mu_i)$ is a convex function of the regional mitigation rate μ_i, with regional coefficients that reflect current carbon intensities and are projected into the future with modest convergence assumptions analogous to those for TFP. We denote by carbon price the marginal cost of mitigating a ton of Carbon.[7]

What is specific to NICE is the representation of sub-regional heterogeneity by attributing regional output to population quintiles by income. We use a fixed savings rate, equal in every region and period, denoted by *s*. Regional average per-capita consumption is

$$\bar{c}_{it} = \frac{1-s}{L_{it}} Y_{it} \quad (3)$$

In NICE, pre-mitigation cost, pre-climate damage, per-capita consumption of quintile *j* is given by

$$c_{ijt}^{pre} = 5\bar{c}_{it} \left(\frac{1+D_{it}}{1-\Lambda_{it}}\right) q_{ij} \quad (4)$$

[6] More precisely, we run a "globally aggregated" version of the model in which all individuals in all regions are assumed to consume the global average consumption. For the logarithmic utility which we use ($\eta = 1$) the Negishi-weighted optimal policy is identical to the globally aggregated optimum. In this sense, a Negishi-weighted regional model gets a single global carbon price by ignoring distributional issues. See Anthoff 2009 for this result.

[7] A detailed description of the RICE model, as well as the DICE model, on which it is based, can be found in Nordhaus 2010 and Nordhaus & Sztorc 2013.

where q_{ij} is the income share of quintile *j* in region i.[8]

Post-mitigation cost and post-damage average per capita consumption (of quintile *j* in region *i* at time *t*) is given by

$$c_{ijt} = \frac{5\bar{c}_{it}}{1-\Lambda_{it}}\Big((1+D_{it})q_{ij} - (1-\Lambda_{it})D_{it}d_{ij} - (1+D_{it})\Lambda_{it}e_{ij}\Big) \quad (5)$$

where e_{ij} is the share of mitigation cost and d_{ij} is the share of damages of quintile *j* in region i. These quintile shares of mitigation cost and damage are computed for different values of elasticity parameters ξ and ω such that[9]

$$d_{ij} = k_{i\xi}q_{ij}^{\xi};\; e_{ij} = k_{i\omega}q_{ij}^{\omega}. \quad (6)$$

This implies a constant elasticity relationship for the quintile mitigation cost and damage shares as a function of income. By modifying the parameters ξ and ω, we are thus able to vary the distribution across quintiles of mitigation cost and climate damages.

To illustrate the meaning of ξ (and ω), consider an 'economy' comprised of two (equally populous) consumption groups A and B, with A consuming USD 4,000, and B USD 40,000 a year. If this `economy' suffers 5% damage from climate change, they jointly lose USD 2,200. If ξ = 1, A loses 200 and B loses 2,000. If ξ = 0, both A and B lose 1,100. If ξ = -1, A loses 2,000 and B loses 200. B goes from losing 5% to 2.75% to 0.5%, while A goes from losing 5% to 27.5% to 50% of pre-damage consumption. (Similar remarks apply to ω.)

The distribution of damages, and thus the value of ξ, depends on where and how the climate changes and modifies the ecosystem at a sub-regional level, on how vulnerable the populations are given the organization of the economy and the infrastructure set-up, and on policy response.[10] The value of ξ has not received much scrutiny so far in the empirical literature, perhaps partly due to the fact that the importance of this parameter had until recently not been demonstrated. However, many studies argue that the poor will disproportionately suffer from climate change (Hallegatte et al. 2016, Oppenheimer et al. 2014, Mendelsohn et al. 2006, Leichenko & O'Brien 2008, Cutter et al. 2003, Kates 2000), meaning that ξ is likely to be less than 1, and might even be negative (in particular in the case of health and mortality impacts). We consider that a relevant range for ξ in the present investigation, is from -1 to $+1$.

The distribution of mitigation cost, and thus the value of ω, is even more dependent on policy decisions. Several studies (Krey 2014, Daioglou et al. 2012, Riahi et al. 2012, Bacon et al. 2010) analyze the share of energy in household expenditures and conclude that an increase in energy prices will hit the poor more than proportionally in the absence of compensatory measures, at least in developed nations.[11] This suggests a value of ω less than 1 (but greater than 0) for a carbon tax

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[8] These regional quintile shares are computed by aggregation of the national quintile shares provided in the World Bank Development Indicators (World Bank 2014).

[9] For equation (6), the parameter values $k_{i\xi}$ and $k_{i\omega}$ are chosen such that $\sum_j d_{ij} = 1$ and $\sum_j e_{ij} = 1$ respectively. This ensures that only the distribution, and the not total amounts of cost and damage, are modulated by the elasticity parameters.

[10] Note that the measurement of damages itself has both empirical and ethical dimensions: valuing losses to different parts of the income distribution in the wake of climate change depends both on relatively objective data on property damage, capital losses, etc., and the more ethically challenging questions regarding valuation of loss of life, health, and livelihood.

[11] The papers in Sterner 2012 suggest that even without compensatory measures, a carbon tax in developing nations might not be regressive.

alone with no compensatory measures. Several other studies (Cullenward et al. 2014, Williams et al. 2014, Sterner 2012, Metcalf 2009) agree with the studies just cited, but also conclude that if an increase in energy prices is combined with compensatory measures it need not disproportionately hit the poor, and could even make all but the highest quintile net beneficiaries – for example, if the compensatory measures involve equal per capita redistribution of the revenues from a carbon tax.[12] In light of this, we consider that a relevant range for ω is from 0 to 2, the latter value being obtained when the cost is borne more heavily by the rich.

Results: Welfare Gains from Representing Inequalities and Allowing Different Regional Prices

In previous work (Dennig et al. 2015) we show with our co-authors that the value of ξ is of great importance to climate policy. For example, if damages are distributed inversely proportionally to income, optimal mitigation effort under the discounting and inequality aversion assumptions of Nordhaus 2010 is equivalent to optimal mitigation in the more aggregated RICE model under the much lower discounting and inequality aversion assumptions of the Stern Review (Stern 2006).

Here we stress that allowing different carbon prices in different regions of the world is another important way in which a utilitarian improvement can be achieved by being sensitive to the interests of the poor, especially when combined with careful consideration of the sub-regional distribution of damages and mitigation cost. As an indication of the importance of these factors, especially the magnitude of the effect on the optimum that allowing differential prices can have, consider the following (Figure 1), which compares the range of optimal prices under the harmonized-price constraint (left-most panel, Figure 1a, showing optima in NICE under a wide range of different mitigation cost and damage distribution assumptions) to the optimum with differential regional prices (middle graph, Figure 1b, showing the wide range of different regional prices given discounting assumptions ρ=2% and η=1, and proportional sub-regional mitigation cost and equal absolute sub-regional damage distributions).[13] Figure 1c shows the temperature paths relative to pre-industrial levels for the policies in Figure 1a and Figure 1b.

[12] As a consequence, progressive compensatory measures can also arguably improve the political feasibility of carbon taxes, at least as measured by percentage of voters who are net beneficiaries of the policy.

[13] We use a relatively high value ρ=2%, and a relatively low value η=1 throughout. For comparison, Stern 2006 used ρ=0.1% and η=1, and Nordhaus & Sztorc 2013 use ρ=1.5% and η=1.45. Increasing ρ reduces all prices. Increasing η spreads the prices in the differential price optimum (Fig 1b) even more, and makes the welfare effects reported in Figure 2 slightly greater. Using η=1, which is at the lower end of the primary range of disagreement, underestimates the difference between the regional price optimum and the harmonized price optimum.

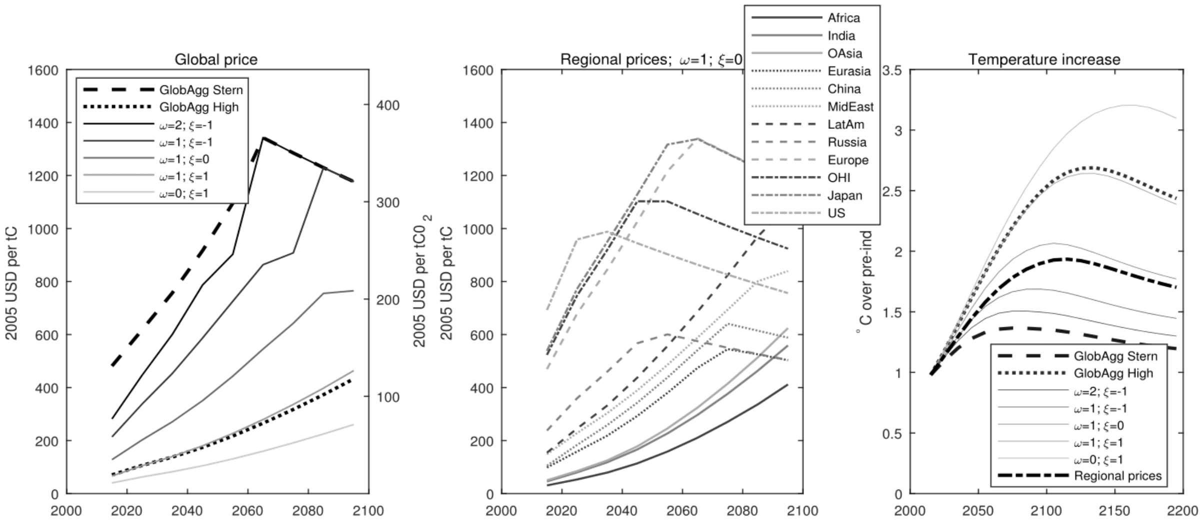

Figure 1: (a) Optimal carbon prices in NICE with harmonized global carbon prices for different combinations of the income elasticity of mitigation cost (ω) and damage (ξ), all for the discounting assumptions ρ=2% and η=1: the prices increase with increasing ω and with decreasing ξ. Also shown are the optimal policies when all regions (and quintiles therein) are assigned the average global consumption (essentially our implementation of DICE, or RICE with Negishi weights) with Stern's discounting assumptions (Global-Stern, with ρ=0.1% and η=1), as well as alternative higher discounting assumptions (Glob Agg, with ρ=2% and η=1). (b) Optimal carbon prices in NICE allowing differential regional carbon prices given higher discounting assumptions (ρ=2% and η=1) and with proportional distribution of mitigation cost and equal absolute distribution of damages within regions (i.e. ω=1 and ξ=0). (c) Temperature relative to preindustrial levels in the optima reported in (a) and (b), where 'Regional Prices' refers to the global temperature path under the optimum in (b). Note that the temperature paths for ω=1; ξ=0 and Regional Prices are for runs that involve the same assumptions about discounting as well as mitigation cost and damage distribution (ρ=2%, η=1, ω=1, and ξ=0), but differ only in that the former but not the latter impose harmonization as a constraint.

As the comparison between the carbon prices in Figure 1a and 1b demonstrates, the effect on optimal policy of allowing differential regional carbon prices can be large; Figure 1b shows the regional carbon prices that emerge from the assumptions behind the middle (ω=1 and ξ=0) line in Figure 1a when the harmonized-price constraint is removed. This comparison shows that even holding fixed the other assumptions of RICE including discount rates but merely allowing differential regional prices leads to optimal carbon prices in several rich regions that are higher than they would be in a globally aggregated model with the discounting assumptions of the Stern Review, and in the poorest region are significantly lower than they would be in a globally aggregated model with equivalent discounting assumptions (ρ=2%, η=1). The effect on optimal policy of imposing a harmonized price can be quite large, and so the question of whether to allow different carbon prices across regions or insist on a globally harmonized carbon price is not merely a theoretical curiosity.

The main regional difference driving the heterogeneity in prices is the difference in TFP and capital stocks, since these determine the vastly different consumption levels. Greater consumption levels imply lower disutility from abatement cost, thus resulting in higher marginal abatement costs (carbon prices) in richer regions. This is the effect described in Chichilnisky & Heal 1994. In our model the aggregate disutility to the region also depends on the sub-regional income distribution, along with the distribution of costs across the sub-regional income quintiles. When mitigation cost is distributed more regressively than in proportion to income ($\omega < 1$) a given amount of mitigation cost will result in greater aggregate disutility in a more unequal region, thus reducing the optimal carbon price in that region relative to what it would be if there was no inequality in that region. A similar argument gives the converse when mitigation cost is distributed more progressively than in proportion to income ($\omega > 1$). In this way, different average regional consumption levels *and* the distribution of consumption have a first order effect on the carbon prices at the optimum. The mitigation cost functions Λ_i are also different across regions, which implies that at a given price two regions would bear different costs, leading to a (second order) level effect on the optimal carbon prices.

To compare the welfare effects of the different policies we measure the welfare gains over business-as-usual (BAU) welfare levels. In our model the BAU runs are simply the model runs with zero carbon prices.[14] The welfare loss from using a policy that ignores distribution altogether (the "Global" policies) or one that considers the distributional impacts, but is constrained to a globally harmonized price depends on the distribution of costs and damages (ω and ξ) and can be quite large.[15] In Figure 2 we show the gain in welfare over business-as-usual, as a percentage of BAU consumption, from implementing the "Global" policy (GlobAgg High path in Figure 1a), the harmonized-price optimum, and the differential-price optimum, *for different values of* ω and ξ.[16]

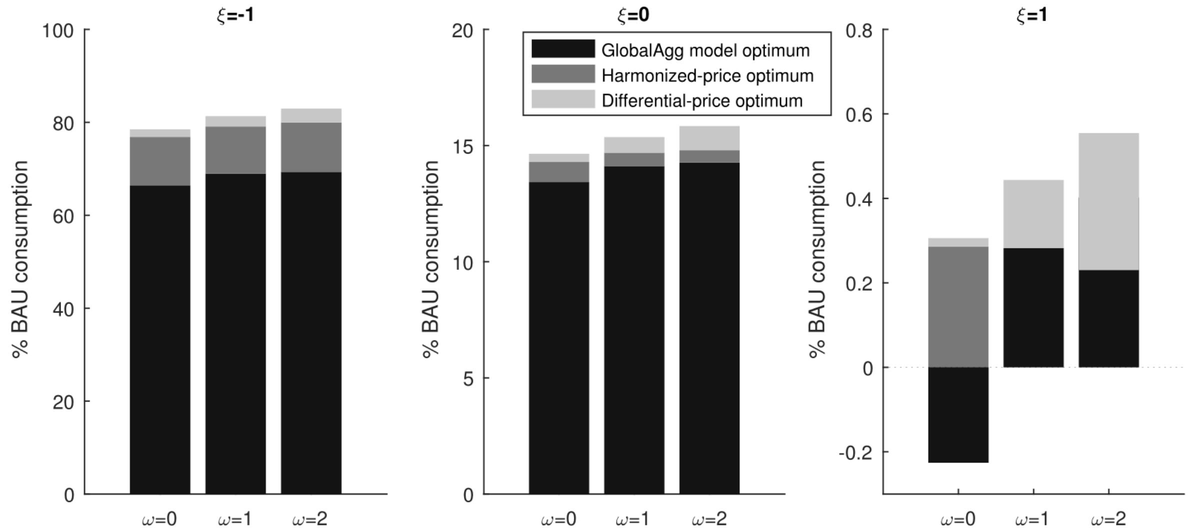

Figure 2: All three bars in all three panels plot the same three stacked quantities: the welfare gain over business-as-usual of implementing the "Global" policy, the harmonized-price optimum, and the differential-price optimum. The "Global" policy consists of the same carbon price path for all 9 bars, whereas the harmonized-price and differential-price optima are computed optimally for the corresponding (ω,ξ) pair. All outcomes assume ρ=2%, η=1. Notice that if ω=0 and ξ=1, using the policy recommended by the globally aggregated model results in a *loss* relative to BAU. This is because at that particular distribution of costs and damages the "Glob Agg-High" optimum *over-mitigates*. At such a high carbon price the loss to the mitigators is greater than the gain in avoided damage. This is visible in Fig 1a, as the price path for "Glob Agg-High" is greater than for "ω=0; ξ=1".

Assuming that both sub-regional mitigation-cost and damage are proportional (ω=1 and ξ=1) the gain over BAU of the Global and harmonized-price optima is 0.3% of consumption equivalent welfare (note that these two policies are almost identical in Figure 1a). The gain over that by allowing

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[14] Since we use a fixed savings rate rather than one which maximizes the overall welfare level, our notion of BAU does not contain an amount of mitigation-by-savings-rate, as described in Rezai, Foley, & Taylor 2012.

[15] It also depends on the discounting parameters. Figure 2 reports the results for ρ=2% and η=1. If η is greater, then the welfare gains (from allowing differential prices) is larger.

[16] The quantity plotted in Figure 2 is the gain in welfare over BAU as a proportion of BAU welfare, measured in consumption units. If W_{BAU} is BAU welfare, as computed by (1), and W_P is the welfare at for some policy *P,* then Figure 2 plots $(W_P^{\frac{1}{1-\eta}} - W_{BAU}^{\frac{1}{1-\eta}}) / W_{BAU}^{\frac{1}{1-\eta}}$.

differential prices is another 0.2%. So allowing for differential prices almost doubles the welfare gain over BAU relative to the Global policy, if we assume that sub-regional costs and damages are proportional to consumption.[17] If we assume instead (see Mendelsohn et al. 2006, Hallegatte et al. 2016), that damage is distributed equally across income groups (ξ=0) while mitigation cost is still proportional, then the Global policy already provides a large proportion of the possible gain. However, the gains are almost two orders of magnitude greater, and the differential-price optimum yields an additional 1% welfare gain over BAU relative to the harmonized-price optimum, and additional 2% over the Global policy. These are large utilitarian welfare gains that are left on the table by focusing only on harmonized-price optimal or Global optimal policies.

We have run Figures 1 and 2 corresponding to alternative values of ρ and η. Since the effect of ρ is to discount the future, regardless of the spatial distribution of outcomes, increasing ρ simply reduces the price paths. Since the effect of increasing η is to increase the sensitivity to distribution, the effect is that for higher values the results corresponding to Fig 1b have more spread out carbon prices across the regions. We also find that the welfare effects in Fig 2 are slightly greater for larger values of η. We also look at versions of Fig 1b for different values of ξ and ω. Lower values of ξ lead to higher carbon prices overall. Higher values of ω also lead to higher prices. As discussed above, alongside the other determinants of the structure of the differential price optimum, ω affects the relative magnitude of carbon prices for regions with different degrees of inequality. For example, India, which has relatively low levels of inequality has significantly higher carbon prices than Africa when $\omega = 0$, however, when $\omega = 2$ India and Africa have almost identical carbon prices. Overall this effect is small when compared with more modest changes in the value of η, even for the sizeable change from $\omega = 0$ to $\omega = 2$. Still the *overall* effect of changing the elasticity parameters on the carbon prices is high, and as shown in Figure 2, the welfare implications of getting the policy wrong depends importantly in those elasticities.

Discussion: Differential prices and international climate policy

The first principle of the United Nations Framework Convention on Climate Change (UNFCCC) states that "The Parties should protect the climate system for the benefit of present and future generations of humankind, on the basis of equity and in accordance with their common but differentiated responsibilities and respective capacities. Accordingly, the developed country Parties should take the lead in combating climate change and the adverse effects thereof" (United Nations 1992). In context, this implies that respect for equity and common but differentiated responsibilities (CBDR) are part of the objective of the UNFCCC as agreed by the parties to that convention, where those values of equity and CBDR are meant to be weighty values that should not be traded off lightly in pursuit of the concurrent goals of protecting current and future generations with climate policy.

In light of this objective, a natural focal point for optimal policy in the absence of large international transfers is the welfare maximizing differential regional prices optimum explained and computed in previous sections. In contrast, imposing a globally harmonized carbon price in the absence of large transfers would result in a sub-optimal outcome by the lights of the UNFCCC, since it requires developing nations to make welfare sacrifices in the pursuit of further cost minimization that are

[17] If we assume $\eta = 1$, when costs are distributed proportionally (ω=1 and ξ=1), the regional distribution does not affect the optimal policy. This is because with such a (logarithmic) utility function, the marginal utility of any income group is proportional to one over its consumption. In this case the marginal utility of a unit of damage (or mitigation cost) to the average consumer is the same as the same unit of damage, distributed proportionally over all income groups. That is to say, proportional cost and damage distributions lead to the same polices as models that aggregate at the regional level.

larger than the welfare gains elsewhere that result from those further moves toward cost minimization.

Because the differential prices optimum is a natural focal point for understanding optimal forward-looking[18] CBDR without increased transfers from rich nations to poor, it can also serve as a 'CBDR baseline' to judge whether alternative policies are improvements for all nations over this constrained baseline: insofar as rich nations prefer to move toward harmonized prices they must at least then compensate for any welfare loss relative to this CBDR baseline that might otherwise be implied for developing nations.[19] In this way, the differential prices optimum can be used as a baseline to evaluate whether particular alternative approaches that combine harmonization with progressive instruments (e.g. a global cap and trade system with a progressive allotment of permits) would also satisfy the UNFCCC objective, because the differential prices optima, again, reflects the utilitarian weighting of the interests of developing nations: one possible interpretation of the CBDR terms articulated in the convention, unlike welfare weightings that ignore distributional issues.

For example, Pareto improving transfers, whereby rich nations pay-off poorer nations in order to emit more, are a much touted mechanism for rich nations to meet their obligations while assisting poorer nations financially for their (additional) mitigation efforts. The clean development mechanism of the Kyoto Protocol is just such a mechanism. They are based on the fact that once obligations in different regions have been established, differences in marginal abatement costs may be quite large, and mutual gains may be achieved by a region with lower cost using less than what is required by its obligation, and thereby allowing the richer nation to pay it in order to emit more. The result is a mutual gain whereby the same global emissions level is still achieved. In the context of Table 1 below, this would allow to the US to persist in emitting substantial amounts of carbon in 2035, but it would have pay India or a country in Africa for the privilege to do so.[20] Notice that for such a mechanism to work, mitigation obligations must be previously established. We claim that the differentiated price optimum could serve such a purpose and is a natural focal point given the objective stated by the UNFCCC.

Of course, the addition of such a trading scheme would imply some regional transfers. However, these transfers would leave regional differences in wealth largely undisturbed, as they are not the massive transfers suggested by general cosmopolitan redistributive aims, but merely the transfers

[18] Here and in what follows, our modeling and discussion focuses only on ‘forward-looking’ considerations (namely, future welfare consequences), and so sets aside ‘backward-looking’ considerations such as historical responsibility that are relevant to optimal policy according to many normative frameworks, including some interpretations of CBDR. In setting aside backward-looking considerations, we do not intend to take a stand on whether they are actually relevant to optimal policy – our thought is merely that (a) it is much more controversial whether they should be included in the climate policy objective, (b) they are not uncontroversially recognized as relevant by the UNFCCC objective, and (c) if they are included in the objective this would tend to move optimal policy even further in the direction we are arguing, so proponents of backward-looking considerations can simply add a further adjustment on top of our calculation of the forward-looking considerations. (Similar remarks apply to other justice-based considerations, such as giving extra weight (or even lexical priority) to meeting the urgent needs of the global poor, etc.) So, we set aside backward-looking considerations here for ease of exposition, and focus only on forward-looking considerations based on current and future income levels, which are at least a large part of the objective from all normative perspectives.

[19] However, it is important to stress that even if richer nations make these transfers, this might be insufficient in the real world to protect the poor relative to how they would have fared under the differential prices optimum, as transfers from rich nations to poor nations are unlikely to be distributed as intended across income groups, and to a first approximation might predictably only benefit the richest quintile in some developing nations.

[20] These two regions would have the lowest marginal abatement cost at the proposed optimum, as can be seen from Figure 1b.

required by the utilitarian objective once it is decided that cosmopolitan general redistribution will not happen, which must then be taken into account by subsequent policy decisions that have distributional consequences. Furthermore, if the resulting international market in permits is fully competitive, this would result in a globally harmonized carbon price. However, it will be a distinct outcome from the constrained harmonized optimum, as it will have lower emissions, and less of the emission burden will be on the poorest nations. It will be cost efficient, like the constrained harmonized optimum, but a welfare improvement over the differentiated price optimum, which is the baseline from which the cost savings would be made. Unfortunately our model is not equipped to compute the distribution of emissions and global carbon price that would emerge from such a trading scheme. A global general equilibrium model would be necessary for that.

In the absence of such a trading scheme and the equilibration of a global carbon price, differential prices cause a competitiveness differential that could lead to relocation of energy intensive industries. The large literature on "carbon leakage" looks at this issue and policy proposals to counteract the effect. The broad conclusion of this literature is that there are two channels for leakage – competitiveness differences due to carbon price differences, and fossil fuel price level reductions due to decreased global demand. The consensus is that the second, price level, effect is the dominating one.[21] The corollary of this insight is that border tax adjustments (BTAs), which correct for competitiveness differences, therefore do not help avoid most of the leakage. However, these models presume unilateral emissions reductions in some regions, and equilibration of demand by other regions (increases) that impose no cap at all. This is the source of the price level effect. A differential price optimum requires different effort in different regions, but does impose a cap on all regions, meaning that the level effect is shut down as a channel for leakage, leaving only the competitiveness channel. We know of no global general equilibrium model that evaluates the competitiveness effect for a global policy with differential prices and the BTAs required to shut down leakage. Such a complementary analysis would be important to flesh out this global policy proposal.

Finally, the differential prices optimum can also be used to judge national commitments in the emerging post-Paris international climate regime, in which the international community has pivoted to a bottom-up approach and international cooperation via nationally determined contributions (NDCs). In this regime, there is a fundamental need to judge the adequacy of national commitments relative to a context in which it is common knowledge that they do not collectively add up to a globally optimal level of mitigation. Because the differential prices optimum can be used to calculate the welfare-optimal shares of emissions, these shares are then also a natural focal point for judging the adequacy of shares of a given level of global emissions reductions, even if that global level is itself suboptimal. These shares can serve as a focal point for the negotiated relative contributions of nations as they gradually deepen their commitments in coming decades.

	η=1; ω=1; ξ=0		**η=2; ω=1; ξ=0**		**η=1; ω=0; ξ=0**		**η=1; ω=1; ξ=1**		**Population Shares 2035**
Region (%)	*H P*	*D P*	*H P*	*D P*	*H P*	*D P*	*H P*	*D P*	
Africa	4	6	4	12	4	6	4	5	16
India	9	15	9	23	9	12	9	12	18
Other n-OECD Asia	9	15	10	25	9	13	9	12	16
Non-Russia Eurasia	2	2	1	3	2	3	2	2	1.9
China	22	29	20	18	23	28	24	28	17
Middle East	10	12	10	9	10	12	10	11	7.8
Latin America	7	8	7	9	7	8	7	7	8.4

[21] See Monjon & Quirion 2013, Lockwood & Whalley 2010, Aldy & Pizer 2009, and Felder & Rutherford 1993 for examples.

Russia	3	2	2	0	3	2	3	3	1.5
OECD Europe	11	6	11	0	10	8	10	8	6.3
OHI	6	2	6	0	5	2	5	4	1.8
Japan	4	2	4	0	3	2	3	2	1.4
USA	15	0	15	0	15	4	15	6	4.4

Table 1: Optimal regional emission shares and world totals for industrial carbon emissions in 2035. Each pair of columns contrasts the emission shares under the harmonized and differential price optima. The first column assumes logarithmic utility and the mitigation and damage cost distributions from the middle panel in Fig. 1. This is our reference scenario. Each other column pair changes one of those three parameters. The pure rate of time preferences is fixed at $\rho = 2$ in all columns. Notice that increasing η has a large effect on spreading the distribution of optimal emission shares, to the point where the richest 4 regions emit zero by 2035. Decreasing the mitigation cost elasticity and increasing the damage elasticity have similar effects: they increase the overall global emissions allowing the richer regions a greater share of that increase relative to our reference scenario.

Table 1 shows the difference between the harmonized price optimum and the differentiated price optimum in terms of shares of industrial CO2 emissions in 2035. In our reference scenario the harmonized price optimum emits 6.5 Gigatons of carbon while the differentiated price optimum emits 5.1 Gigatons of carbon.[22] As reductions from the 11.7 Gigatons in business-as-usual, the total mitigation effort is not too different in the two optima. However, the distribution is radically different. For example, in the harmonized price optimum, the US and Europe would continue to cause 15% and 11% of total emissions while India and Other (non OECD) Asia would only cause 9% of emissions each. In the differentiated price optimum the US would be expected to have (net) zero percent of emissions and Europe 6%, while the two developing regions would be emitting 15% of global emissions each.

Conclusion

In sum, a differential prices optimum is generally welfare superior to the harmonized global prices optimum produced by standard IAMs. While it is often stated that optimal global climate policy requires global harmonization of marginal abatement costs, this is only the case if distributional issues are ignored, or if lump-sum transfers are made between countries.

As our results indicate, the welfare gain and change in global mitigation effort from allowing different regional prices depends on model parameters, in particular the two income elasticities which determine how mitigation costs and climate damages are distributed across income groups within regions. We find that the effect on optimal policy of allowing different regional prices can be large, even for the relatively low value of 1 for the elasticity of marginal utility.

A differential prices optimum is also a natural focal point for climate policy that gives proper weight to common but differentiated responsibilities and respective capacities, and for judging the relative adequacy of national commitments in the emerging 'bottom-up', NDC-focused international climate regime. The resulting gain in welfare is the main argument for grounding policy analysis on the differential prices optimum rather than the welfare inferior harmonized price optimum that ignores distributional issues, as the welfare gain is driven only by the logic of common but differentiated responsibilities and different capacities internal to the climate policy challenge, rather than by general redistributive aims. Once such commitments are established and deemed adequate, international emissions trading can provide further gains still, as in any situation with differential prices the same emissions level can be achieved in a Pareto improving way by allowing a region with a higher price to pay a region with a lower price for a share in the latter's emission share – i.e. an

[22] These are just the industrial carbon emissions that are endogenous in the model.

emissions trading scheme that allocates permits in accord with the emission shares in the differential prices optimum.

In general, when national and subnational inequalities are properly represented it is especially problematic to insist on ignoring the negative welfare effects of imposing harmonized abatement costs as a modeling constraint. Improved representation of these inequalities and recognition of their relevance to climate policy (as in NICE with differential regional prices) should become new best practices in climate economy IAMs.

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