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On Differentiated Carbon Prices and Discount Rates

Abstract

The consensus view amongst economists is that carbon prices, in order to be effcient, must be the same across the globe. But when there are inefficiencies in the allocation of capital so that consumers in different countries face different discount rates, we show that efficient carbon prices must be different across countries. This is a consequence of Hotelling's familiar argument on the price of a non-renewable resource: it must grow at the rate of the next best use of marginal funds, which is equal to the country's discount rate. If different countries discount at different rates, their carbon prices ought to grow at different rates as well. If they grow at different rates, they can't be the same all of the time, as first-best carbon prices are. The computational climate policy literature has so far avoided this conclusion by altering time preferences in a country specific way through time-varying Negishi weights. We show that the use of such weights causes inefficient policy prescriptions and, furthermore, has the particularly undesirable consequence of incorrectly discounting future consumption more in countries with high growth rates. The existence of inefficiencies in the savings process - causing differences in discount rates - is well-known and should be acknowledged head on in climate policy analysis. Doing so results in global mitigation policy with carbon price paths for different countries growing (efficiently) at different rates.

Keywords: carbon price, Hotelling rule, efficient climate policy, Negishi weights, integrated assessment models, discounting.

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1. Introduction

Any meaningful climate mitigation policy will reduce global carbon emissions significantly over the coming decades. Textbook efficiency conditions suggest that the cost of doing so should be chosen so that the marginal costs of emission reductions are the same all over the world and rising gradually over time. The cross-sectional equality of marginal costs and their dynamic structure are interlinked; the marginal costs can only be the same in all countries if they are also growing at the same rate in all countries. The rate at which the marginal costs should efficiently grow is closely tied to inter-temporal discounting. So if some inefficiency keeps countries from all discounting at the same rate, this textbook reasoning no longer holds. In the presence of such inefficiencies, the marginal cost of abatement – or carbon prices – will have to be different across countries in order to be efficient.

We explicitly model inefficient capital allocation in a textbook optimal savings model to demonstrate that different discount rates across countries will alter the dynamic structure of efficient carbon prices, causing them to grow at country specific rates. This is a consequence of the arbitrage argument behind the familiar Hotelling rule for the price of a non-renewable resource – it must grow at the rate of the next best use of marginal funds (Hotelling, 1931). Given the possibility to re-allocate emissions between time periods, the price of reducing a ton of carbon next year must be equal to the price of reducing the equivalent amount today times the discount rate between today and next year. If, due to some friction, different countries have different discount rates, their carbon prices must necessarily grow at different rates. Two prices growing at different rates cannot be the same all of the time, so it is inefficient to apply a uniform global carbon price at all times in all countries in such a context.

Our result is a typical instance of a second-best policy argument à la (Lipsey and Lancaster, 1956). There is a large literature on second-best environmental policy, which is focused mostly on optimising the implementation of a carbon price *within* a jurisdiction given existing price distortions – or wedges – in the fiscal system. The literature distinguishes between the "revenue-recycling effect" – whereby carbon tax revenue could yield a double dividend by replacing inefficiencies due to other taxes – and the "tax-interaction effect" – whereby the efficient level of the carbon price is affected by existing distortions in the tax system.[1] We tackle an analogous question to the tax-interaction literature, but in the context of the efficient distribution of carbon prices across countries rather than within the fiscal structure of a single jurisdiction. Like that literature, we find that an existing inefficiency (in our case in the savings process) affects the efficient level of the carbon price.

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[1] Goulder (2013) provides a thorough review of the existing results. Prominent examples are Bovenberg and de Mooij (1994); Parry (1995); Bovenberg and Goulder (1996).

Focused, like us, on the distribution of abatement in a simple multi-country model, Chichilnisky and Heal (1994) tackle a related, but distinct, question. In a static model they show that only one out of all allocations on the efficiency frontier equalizes carbon prices across countries, unless one assumes lump-sum transfers are made between countries. Our dynamic model leads to a stronger conclusion, namely that there is no efficient policy that equates carbon prices at all times if there is heterogeneity in discount rates. Our paper thus provides a simple yet powerful argument that questions one of the cornerstones of the global climate policy debate, namely that efficiency of climate policy requires uniform carbon prices.

A number of studies compute efficient carbon prices with models in which there is country specific consumption growth. The Ramsey equation

$$\varrho_t = \rho + \gamma g_t$$

links the discount rate ϱ_t to the consumption growth rate g_t.[2] Cross-country differences in consumption growth thus imply differences in the discount rate. By our main result, such differences also imply differences differences in the growth rates of efficient carbon prices. But almost all studies with disaggregation at the regional or country level recommend a globally uniform carbon price growing at the same rate in all countries despite having different equilibrium consumption growth rates. Furthermore, this is claimed to be efficient. This is the result of a flawed but widespread modelling approach. Inspired by the original "cooperative" solution in the RICE model (Nordhaus and Yang, 1996), several modelling groups have adopted the solution based on time-varying Negishi weights in some of their publications (for instance (Kemfert and Tol, 2002) with FUND, (Bosetti et al., 2009) with WITCH, and Moore and Diaz (2015) with a derivative of RICE). These time-varying weights achieve global uniform carbon prices despite differences in consumption growth rates by modifying preferences so that they produce uniform carbon prices regardless of the underlying constraints. To achieve this, the pure rates of time preference must be artificially increased in low-growth countries and decreased in high-growth countries. Modified in just the right way, such preferences result in uniform carbon price growth rates, as was the aim of the authors. But the modification of time preference also changes the way in which future climate damages are weighed relative to present mitigation investments. Since the way in which climate damages are discounted is of such importance to the social cost of carbon and thus to the reported optimal mitigation pathway, such ad-hoc alteration of discount rates is particularly undesirable in the context of a climate policy model.[3] The use of time-varying Negishi weights is thus intricately linked to the prescription of uniform global carbon prices in the presence of constraints that would make such a policy inefficient, as we show below. But their use in climate policy models is also independently problematic because

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[2] The pure rate of time preference ρ and the elasticity of marginal utility γ are preference parameters governing intertemporal substitution (Ramsey, 1928).

[3] See Arrow et al. (1996) for an overview of the discounting debate.

they implicitly modify time preference in models where such tinkering with preferences is particularly undesirable. As far as we know, we are the first to show these preference altering side-effects of time-varying Negishi weights.

What our analysis takes as given is that the consumption discount rates are different in different countries, and that consequently the discount rates are heterogeneous. In the standard neoclassical growth framework we use below, debt flows would equalise both interest rates, consumption growth rates and – by the Ramsey equation – the discount rates ϱ_t. So the observed differences in interest rates and consumption growth rates must be due to some friction in the allocation of capital. The reason for the heterogeneity in consumption discount rates (and whether the interest rates are heterogeneous at all) is a matter of significant academic debate. We take no stand on the issue and simply acknowledge that some friction must be at play driving a wedge between the discount rate of average consumption across countries. We implement such a friction in a way that follows the model in Nordhaus and Yang (1996) and interpret it in light of the approach taken in Gourinchas and Jeanne (2013)[4]. Frictions, whatever their cause, appear in the model as wedges between the discount rates in different countries. We apply these wedges without taking a stand on the underlying cause. The literature proposes a variety of potential causes, including expropriation or default risk (Reinhart and Rogoff, 2004), inefficiencies in the production of capital goods (Hsieh and Klenow, 2007; Caselli and Feyrer, 2007), frictions in international capital markets (Monge-Naranjo et al., 2019), local credit market imperfections (Banerjee and Duflo, 2005), or – what the wedges resemble mathematically – taxes on savings.

Observed interest rate heterogeneity is probably best explained by a combination of the enumerated factors. The important feature for our purpose is always the same: a wedge between the consumption discount rates across different countries and its implications on the efficient carbon price growth rates. Our main premise is that these inefficiencies are facts to be acknowledged in the design of efficient climate policy. As we show below the second-best carbon prices in light of these inefficiencies have different growth rates that depend directly on the wedges needed to explain the heterogeneous consumption behaviour.

2. Efficient emissions allocations in a simple multi-country model

Consider I countries, each represented by a single agent i, living T periods, and trading off consumption flows during different periods, c_{it}, via an additively separable, discounted

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[4] Gourinchas and Jeanne (2013) base their framework on Chari et al. (2007).

utility given by

$$U_i = \sum_{t=0}^{T} \beta^t u(c_{it})$$

where the felicity function $u : \mathbb{R}_+ \to \mathbb{R}$ is strictly increasing, strictly concave and differentiable.

Each country produces a single consumption/capital good, which it can consume, invest, or borrow/lend at international capital markets. Production is a function of capital, k_{it}, and the country's emissions, E_{it}:

$$y_{it} = F_{it}(k_{it}, E_{it}) : \mathbb{R}_+ \times [0, \bar{E}_{it}] \to \mathbb{R}_+$$

This specification sees emissions as a productive factor. We restrict the domain of emissions by an upper bound $\bar{E}_{it}$ below which emissions are in fact productive, i.e., below which $F_{E,it} > 0$. We further assume that the production function is twice differentiable, and that $F_{k,it} > 0$ and $F_{kk,it}, F_{EE,it} < 0$ over the whole domain.[5] These assumptions ensure convexity of production which, along with convexity of preferences, ensures the existence of equilibria.

Finally, we also assume that $F_{it}(0, E) = 0, \forall E \in [0, \bar{E}_{it}]$, and $F_{it}(k, E) > 0, \forall k > 0, E \in [0, \bar{E}_{it}]$, as well as the Inada conditions on capital: $\lim_{k\to 0} F_{k,it}(k, E) = \infty$ and $\lim_{k\to\infty} F_{k,it}(k, E) = 0, \quad \forall E \in [0, \bar{E}]$. As usual, these conditions ensure the existence of *interior* equilibria.

We denote net inflows from the world to country i in period t by b_{it}, with negative values corresponding to net outflows. With the inclusion of international flows of capital the resource constraint in country i is given by

$$k_{it+1} = y_{it} + (1 - \delta)k_{it} - c_{it} + b_{it+1}. \tag{1}$$

Naturally, total global borrowing and lending must equal zero in every period, so

$$\sum_{i=1}^{I} b_{it} = 0. \tag{2}$$

Our aim is to highlight a simple conceptual point about the evolution over time of efficient carbon prices in different countries. To that end we will work with the simplest allocation problem that requires a time varying carbon price; the efficient allocation across time and space of a fixed amount of carbon cumulative carbon emissions. Our conclusions would survive the extension to an endogenous atmospheric carbon stock causing a climate change externality and thus damage to future output. But our main point stands out more clearly against the familiar Hotelling rule that results from a fixed cumulative emissions assumption.

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[5] Here $F_{x,it}$ denotes the derivative of F_{it} with respect to x and $F_{xy,it}$ denotes the respective second derivative.

Such an assumption can be rationalised as a desire keep the atmosphere below a temperature threshold, for example.

Total global emissions are

$$E_t = \sum_{i=1}^{I} E_{it}$$

Denoting the stock of atmospheric carbon by S_t the carbon dynamics take a simple linear form.[6]

$$S_{t+1} = S_t + E_t, \tag{3}$$

The main constraint we impost is that the carbon stock remain below an exogenously given maximum, B. We will refer to a distribution of emissions, $\{E_{it}\}_{i \leq I, t \leq T}$, as *admissible* if it ensures that

$$S_t \leq B, \quad \forall t \leq T. \tag{4}$$

According to the bottom up approach espoused by the Paris agreement via the intended nationally determined contributions (INDCs), the emission levels E_{it} are determined by national governments. The reasons governments might have for taking a particular abatement path are various, including responsiveness to environmental preferences of citizens, strategic energy policy considerations, and interlinked negotiating positions in different international forums governing climate and trade policy. In our model there are no private incentives to take any abatement action at all. Instead our approach is to take an admissible distribution of emissions $\{E_{it}\}_{i \leq I, t \leq T}$ as *given*, and evaluate whether the equilibrium that results from such an allocation is efficient. Those allocations that do not result in an efficient equilibrium can reasonably be rejected.

International capital movements are modelled as the equilibrium outcome of savings and inter-temporal trade in capital. Denoting by r_t the interest rate paid on international capital, the international asset position of country i evolves according to

$$A_{it+1} = (1 + r_t)A_{it} - b_{it} \tag{5}$$

For any admissible distribution of emissions, we define an *admissible world equilibrium* in international capital markets as a sequence of consumption, capital, and international asset positions for each country $\{c_{it}, k_{it}, A_{it}\}_{1 \leq i \leq I, 0 \leq t \leq T}$, and a time path of interest rates $\{r_t\}_{1 \leq t \leq T}$,

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[6] Here we implement the simplest case of a fixed carbon stock. This is more restrictive that necessary for our conclusions. Adding removal rates to the atmospheric carbon dynamics would alter the details of the mathematics, but would keep the qualitative conclusions intact.

such that each country's allocation maximises its utility subject to (1), (5), and $A_{iT} = 0$, and so that international financial markets clear: (2). Note that each admissible distribution of emissions results in a *different* admissible world equilibrium.

Under the assumptions made on preferences and production, such an equilibrium exists for any admissible distribution of emissions, and the necessary conditions are the familiar ones. In particular, the consumption Euler equation, and the requirement of efficiency of production plans tie the consumption and capital sequences to the interest rates:

$$\beta \frac{u'(c_{it})}{u'(c_{it-1})} = \frac{1}{1+r_t} \tag{6}$$

$$\frac{1}{1+F_{k,it}(k_{it}, E_{it}) - \delta} = \frac{1}{1+r_t} \tag{7}$$

An admissible distribution of emissions is *efficient* if the resulting admissible world equilibrium is Pareto efficient. The definition results in two necessary conditions on the world equilibrium; relating marginal productivity of emissions - equivalently the marginal cost of abatement or implicit carbon prices – across space and time.

In every period t, the carbon price must be the same in all countries:

$$F_{E,it} = F_{E,jt}, \quad \forall i, j, t < T_B \tag{8}$$

and in each country, the carbon price must grow at the rate of interest:

$$\frac{F_{E,it}}{F_{E,it-1}} = (1 + r_t), \quad \forall t < T_B \tag{9}$$

where T_B is the first period during which the carbon stock has reached the threshold B.

The first condition is so well known that it is provided without proof. The second is, in effect, Hotelling's rule for the optimal use over time of an exhaustible resource. The following variational argument, due to Hotelling (1931), establishes the necessity.

Hotelling's variational argument. *Consider an admissible distribution of emissions and resulting admissible world equilibrium such that for some country i, $F_{E,it} < F_{E,it-1}(1 + r_t)$. If emissions are decreased by Δ in period t and increased by Δ in period $t - 1$, for a sufficiently small $\Delta > 0$ the resulting distribution remains admissible. This is true as long as Δ small enough so that the carbon budget isn't reached at the beginning of period t on account of the additional Δ emissions at $t - 1$. Such a shift in the timing of country i's emissions results in a first order gain in output of $\Delta F_{E,it-1}$ in period $t - 1$, and a loss of $-\Delta F_{E,it}$ in period t. Whether or not that is an improvement to country i depends on its marginal rate of substitution between those two periods – the discount rate – which in equilibrium is equal* *to* $1/(1+r_t)$ *by condition* (6)*. The net effect on country* i*'s utility is*

$$\Delta F_{E,it-1} - \Delta F_{E,it}\frac{1}{1+r_t} > \Delta F_{E,it-1} - \Delta F_{E,it-1}(1+r_t)\frac{1}{1+r_t} = 0 \tag{10}$$

The inequality is due to the assumption that $F_{E,it} < F_{E,it-1}(1+r_t)$*.*

Since the altered distribution of abatement remains admissible, and comes at no cost to other countries, the demonstrated improvement for country i *establishes a Pareto improvement. The case when* $F_{E,it} > F_{E,it-1}(1+r_t)$ *is shown analogously.*

The essence of the argument is that gains can be achieved via the intertemporal reallocation emissions unless the marginal productivity of emissions grows at the discount rate. Combined, the two conditions require an admissible distribution of emissions that result in carbon prices that are the same in all countries, and grow uniformly at the international interest rate r_t.

2.1. **Second best emissions allocations with imperfect capital markets.** The previous section reviews the well known results that in order to be efficient, emissions must be allocated in a way that equates their marginal productivity across all users, and so that the marginal productivity grows at the rate of interest.

The result on the growth rate highlights the role played by the intertemporal allocation of the consumption good in determining the growth of the carbon price. If the marginal rate of substitution (MRS) between consumption in two periods is greater than the growth rate in the cost of reducing a ton of emissions – the carbon price – then it is advantageous for the country to delay some emissions. In this section we consider equilibria in which the MRSs differ across countries. In such a situation, the incentives to delay or bring forward emissions differ across regions, making the inter-temporal allocation of emissions efficient at different carbon price growth rates in different countries.

Of course, a situation in which an MRS differs across countries is an inefficient situation to begin with, since countries could trade in the good they value relatively less for the good they value relatively more. But that is just the – well known – situation in international capital markets. Average interest rates – a measure of the MRS if internal capital markets operate efficiently – and consumption growth rates – linearly dependent on the MRS under by the Ramsey equation – differ significantly across jurisdictions.[7] This observed inefficiency has

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[7] The literature on international capital flows in particular is deep and sophisticated. Notably Caselli and Feyrer (2007) claim that, correctly measured the marginal product of capital doesn't exhibit systematic bias, while Monge-Naranjo et al. (2019) claim the opposite.

many possible causes, all of which have similar implications on the equilibrium conditions, namely wedges between individual countries' MRSs and the prevailing interest rates.

A large literature studies the causes of these wedges and the entirety of development finance makes it its goal to overcome them. In what follows we take the underlying financial market inefficiencies as given, and simply accept that there will be wedges causing the marginal rates of substitution not to be equalised across countries. In doing so, we do not wish to minimise the importance of efforts to reduce these underlying inefficiencies. They are of significantly greater magnitude than the second best inefficiency resulting from equalised carbon prices that we illuminate here. But the effort to address frictions in international capital markets is already underway, while their implications for second best carbon prices that we show here is not even well understood.

There are a number of ways to model the presence of wedges in the inter-temporal allocation of consumption. The simplest approach, taken here, is to assume constraints on the net level of international assets countries can hold. Recall from (5) that A_{it} is the international asset position of country i in period t. In the simplest case we can assume exogenous lower bounds on negative assets $\bar{A}_{it} < 0$ such that

$$A_{it} > \bar{A}_{it} < 0 \tag{11}$$

If such a constraint binds for a particular country, it means that any further capital that could beneficially flow to the country is prevented from doing so. As a consequence of such a binding constraint the country will be left valuing current consumption over future consumption at a higher rate than other countries at which the constraint doesn't bind.

Formally, for any admissible distribution of emissions we define the *admissible constrained equilibrium* in analogy to the admissible world equilibrium by requiring (11) in addition to (1), (5), and $A_{iT} = 0$.

The equilibrium conditions for any admissible world equilibrium are given by (6) and (7). The analogous conditions for the admissible constrained equilibrium are

$$\beta \frac{u'(c_{it})}{u'(c_{it-1})} = \frac{1 - w_{it}}{1 + r_t} \tag{12}$$

$$\frac{1}{1 + F_{k,it} - \delta} = \frac{1 - w_{it}}{1 + r_t} \tag{13}$$

where w_{it} is positive during periods in which (11) binds and zero otherwise.[8] Thus, when the constraint binds, the country discounts the future at a higher rate than the prevailing

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[8] With our chosen source of constraint, $w_{it} = \phi_{it}/\lambda_{it}$, where the λ are the Lagrange multipliers on (1) and the ϕ are the multipliers on (11). Under an alternative specification the exact definition of w_{it} will vary.

interest rate r_t, and would want to borrow (decrease it's negative international asset position further) but is prevented from doing so.

The constraints (11) are admittedly ad-hoc and unlikely to reflect the actual processes holding up capital accumulation in countries with high interest rates and consumption growth rates. Our results below do not depend on this exact form of capital market inefficiency, but rather on the presence of non-zero wedges w_{it}, which could exist for a large number of more realistic reasons.

By the Euler equation (12) we could simply take the observed cross-country differences in consumption growth rates on the left hand side to imply the existence of wedges on the right hand side. Such is the empirical approach taken in Gourinchas and Jeanne (2013), which we could have followed by simply postulating wedges of a certain magnitude, without specifying their cause. In this sense, the constraints (11) are just a modelling convenience to generate the wedges w_{it}, and needn't be taken literally as their cause.

How do the w_{it} affect the efficiency of admissible emission distributions, previously determined by (8) and (9)? Recalling the inequality (10) which constitutes the variational argument establishing conditions (8) and (9), the situation is inefficient unless

$$\Delta F_{E,it-1} = \Delta F_{E,it} \times MRS_{t-1,t}.$$

In the situation covered by Hotellings variational argument on page 7 the $MRS_{t-1,t} = 1/(1+r_t)$. In the situation with wedges discussed here, the argument is identical, except that $MRS_{t-1,t} = (1-w_{it})/(1+r_t)$.

We state this result formally as a proposition.

Proposition 1. *If an admissible constrained equilibrium features non-zero wedges w_{it}, then Pareto improvements are possible by re-allocating country i's emissions across time unless*

$$\frac{F_{a,it}}{F_{a,it-1}} = \frac{1+r_t}{1-w_{it}}, \quad \forall t < T_B, \tag{14}$$

where T_B is the first period in which the carbon budget is reached.

The direct implication of Proposition 1 is that wedges in the Euler equation will lead to wedges the carbon price growth rates if a country's emissions are allocated efficiently across time. The following simple calculation judges the quantitative impact on the divergence of efficient carbon prices of accounting for differences in discount rates. Assume the felicity function has a constant elasticity of substitution, $u(c) = (c^{1-\gamma} - 1)/(1-\gamma)$, with $\gamma = 1.5$.[9]

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[9] This is a approximately the mean amongst the values assumed by experts on climate policy Drupp et al. (2018).

The difference in the per capita consumption growth rate between India and the USA since 1980, for example, has been approximately 3% per annum. Using (12) to estimate the wedge between the two countries this implies a 4.5% per annum difference in carbon price growth rates. Had carbon prices been efficiently applied in the last 30 years. Even if the difference in consumption growth rates narrows significantly in the future as convergence runs its course, an annualised difference of at least 1% – with an implied wedge of 1.5% – might be expected over the coming decades.

If they grow at different rates, carbon prices in different countries cannot remain the same. A difference of 1.5% over accumulated 50 years amounts to 210%. If carbon prices were to be equalised at full mitigation in 2070, the carbon price in India would have to be less than half what it is in the US in order to be efficient. This stands in stark contrast to the commonly advocated equal carbon price prescription.

As mentioned above, this result is only predicated on the existence of country specific wedges, w_{it}, and not on the particular type of constraint on foreign assets that we impose. There are, in fact, many possible reasons for the existence of such wedges. The usual credit market imperfections invoked in the literature on international capital movements, such as expropriation risk, sovereign default risk, bureaucracy and corruption, fit the bill. Country specific iceberg costs in installing physical capital similarly result in non-zero w_{it}, which would also have resulted in these implications.

3. Regional models and uniform carbon price prescriptions

A number of computational models of climate change assume that consumption growth is different across the model countries/regions. But the theoretical point we just made in Proposition 1 – that such different consumption paths ought to lead to different carbon price paths – has not been raised in any of them.

This is in part due to a widespread solution procedure, proposed in Nordhaus and Yang (1996) as the cooperative solution, which cancels the result we just presented. The original paper acknowledges that much. Having imposed constraints against international capital flows in their optimisation model in order to maintain different consumption growth rates in equilibrium, the authors found that their "algorithm will not produce the *necessary* complete price equalisation for carbon".[10] They seem to presume *a priori* that carbon prices ought to be equalised, and set about to modify their solution concept in order to get such an outcome. We briefly explain what they did, why it is wrong, and how it matters to climate policy.

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[10] Nordhaus and Yang (1996) pg. 747, our emphasis.

For simplicity of exposition, in this section we will assume throughout that the felicity function is $u(c) = (c^{1-\gamma} - 1)/(1-\gamma)$.

According to a result due to Negishi (1960) weights $\{\alpha_i\}_{i \le I}$ can be chosen so that the optimum of

$$\sum_{i=1}^{I} \alpha_i \sum_{t=0}^{T} \frac{1}{(1+\rho)^t} \frac{c^{1-\gamma} - 1}{1-\gamma} \tag{15}$$

subject to resource constraints yields the competitive equilibrium subject to a set of initial endowments and the same resource constraints. Following this approach Nordhaus and Yang (1996) cast the optimal mitigation problem as an equilibrium outcome with appropriately assigned property rights to emissions. As quoted in the paragraph above, in order to avoid counter-factual equilibrium foreign asset balances, they impose restrictions of the form (11), and these resulted in an allocation of abatement in which carbon prices are not equalised across countries. In light of Proposition 1 above this is of course not surprising. But rather than offer such an allocation of abatement as the efficient policy, Nordhaus and Yang (1996) do something completely different.

They found that if, instead of solving for optimum of the objective (15), they optimise a different objective altogether, they could get equal carbon prices despite the capital market frictions. The objective their cooperative solution maximises is

$$\sum_{i=1}^{I} \alpha_i \sum_{t=0}^{T} \prod_{\tau=1}^{t-1} \left[\frac{(1+g_{i\tau})^{\gamma}}{(1+\bar{g}_{\gamma\tau})^{\gamma}} \frac{1}{1+\rho} \right] u(c_{it}). \tag{16}$$

where g_{it} is the growth rate of consumption in country i during period t, and $\bar{g}_{\gamma t}$ is the growth rate of the generalised mean of order γ of global consumption,[11] and $\alpha_i = c_{i1}^{\gamma} / \sum_j c_{j1}^{\gamma}$. The parameters α_i, g_{it} and $\bar{g}_{\gamma t}$ depend on the endogenous consumptions and consumption growth rates, but in the optimisation they are held constant. If the resulting optimal consumptions are different from those used in the weights, these values are iterated into the weights until a fixed point is reached. At the fixed point solution the consumptions used in the definition of the weights are in fact the optimal consumption levels given those weights. This fixed point is the time-varying Negishi solution proposed by Nordhaus and Yang (1996).

The solution is not an equilibrium of a model in which the representative agents have preferences given by (**??**). Neither is is an efficient outcome of a model with such preferences.

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[11] The generalised mean of order ζ of a distribution $\{x_i\}_{i \in \mathcal{I}}$ is defined as

$$\bar{x}_{\zeta} = \left[\frac{1}{|\mathcal{I}|} \sum_{i \in \mathcal{I}} x_i^{\zeta} \right]^{\frac{1}{\zeta}}$$

It is increasing in γ, approximating $\max_i\{x_i\}$ as γ goes to infinity.

Instead, the solution represents the Pareto efficient outcomes to a problem in which country i's representative agent has utility

$$\sum_{t=0}^{T} \prod_{\tau=1}^{t-1} \left[\frac{(1+g_{i\tau})^{\gamma}}{(1+\bar{g}_{\gamma\tau})^{\gamma}} \frac{1}{1+\rho} \right] (c_{it}^{1-\gamma} - 1)/(1-\gamma) \tag{17}$$

By comparing (**??**) with (17) one can see that getting from the former to the latter amounts to a modification of time preferences. Instead of having a constant per period pure time discount factors of $1/(1+\rho)$, the modified objectives have pure time discount factors between period t and period $t+1$ of

$$\beta_{i,t,t+1} = \frac{(1+g_{it})^{\gamma}}{(1+\bar{g}_{\gamma t})^{\gamma}} \frac{1}{1+\rho} \approx \frac{1}{1+\rho+\gamma(\bar{g}_{\gamma t} - g_{it})}.$$

Or, as shown in the continuous approximation on the right hand side, one can think of the discount rate as increased by the term $\gamma(\bar{g}_{\gamma t} - g_{it})$.

How does this affect the resulting carbon prices? From Proposition 1 we know that the necessary condition for efficiency of carbon prices is that they grow at the consumption discount rate between the two periods in question which is given by (12). Since in the time-varying Negishi solution the discount factor between t and $t+1$ is given by $\beta_{i,t,t+1}$, replacing β with $\beta_{i,t,t+1}$ in (12) yields the discount rate under time-varying Negishi preferences:

$$\beta_{i,t,t+1} \frac{u'(c_{it+1})}{u'(c_{it})} = \beta_{i,t,t+1} \left(\frac{c_{it}}{c_{it+1}} \right)^{\gamma} = \frac{\beta_{i,t,t+1}}{(1+g_{it})^{\gamma}} = \frac{1}{(1+\rho)(1+\bar{g}_{\gamma t})^{\gamma}}$$

Since the mean growth rate $\bar{g}_{\gamma t}$ is independent of country, the modification of time preferences achieves an equalisation across countries of perceived discount rates, irrespective of constraints that might generate wedges between the actual consumption discount rates, which must still equal $\frac{1}{1+\rho} \frac{u'(c_{it+1})}{u'(c_{it})}$ and are not the same across countries as long as countries are growing at different rates.

We raise this point about the time-varying Negishi weights because they have been an important feature of the computational climate policy literature and have obscured the important result about efficiency that we demonstrate above. But we also take the opportunity to highlight another error they can cause. These weights have as a consequence that the discount rate is incorrectly *reduced* in high growth countries and *increased* in low growth countries. It is well known that small differences in the discount rate make an enormous difference to the social cost of carbon that is often estimated in computational climate models. A difference 1.5% per annum amounts to the difference in the conclusions of Professors Stern and Nordhaus on the urgency of climate action (Stern, 2006; Nordhaus, 2007). Given that differences in consumption growth rates can be quite large (3% per annum between India and the US in the past 30 years), the resulting bias to the social cost of carbon might be an important error.

4. Conclusion

We have shown that the inefficiency that causes heterogeneity in the savings process affects the way we evaluate carbon mitigation policy. A single global carbon price, growing at the same rate everywhere, is inefficient in this second best context, and ought to be discarded in favour of country specific carbon prices, growing in proportion to the consumption discount rate implied by the local consumption growth rate. We find a sort of Hotelling rule, region by region.

As can be deduced from our discussion of time-varying Negishi weights, there is a situation in which such regional differences in carbon prices are not necessary for efficiency even when discount there is an inefficiency in the savings process. That is when time preferences in different regions happen to be modified in just the right way – namely according to (17) – to counter the preference for differently growing carbon prices. Such a modification would be warranted if time-preferences genuinely differed in such a way across countries. But to simply assume a change preferences in order to get uniform carbon prices is to manipulate the input to get one's desired output and puts the cart before the horse.

We argue that this is an important second-best consideration in the formulation of global climate policy. Much of the climate policy research community takes the efficiency of globally uniform carbon prices as given, and a number of initiatives argue for a global climate policy agreement in which countries pay the same opportunity cost for the marginal tonne of CO_2 emissions reductions. But as we have shown this is based on a static view of the problem, and does not account for the dynamic structure of the decarbonisation process, especially in light of incompletely integrated international capital markets.

The correct way to understand our result is that an equilibrium in which emissions are allocated across countries in a way that equalises carbon prices will not be efficient, *if* the equilibrium features cross-country differences in discount rates (or interest rates). What our results cannot speak to is whether trade international trade in emissions permits (from a predetermined allocation in which the price of permits are not equalised) will result in an improvement. In a world without any frictions, that type of trade would result in a Pareto improvement over the previous allocation. In a world with wedges in the interest rate, whether or not trade in permits results in an improvement will depend on how the trade in permits affects the the capital markets and thus the wedges in the new equilibrium. To answer that question we would have to take a explicit stand on the nature of the frictions that cause the wedges, and, furthermore, make an assumption about how trade in permits interacts with the capital market frictions. This is an important question for the formulation of international climate policy that we leave to future research.

Ours is not a result on appropriate carbon prices and abatement effort in light of equity concerns, such as Chichilnisky and Heal (1994); Sandmo (2007); Anthoff and Tol (2010); Dennig et al. (2015); Anthoff and Emmerling (2019). Our argument – being about growth rates of all efficient outcomes – does not eliminate the question of the international distribution of abatement effort. In fact, the question of the overall distribution of effort (how much of the total remaining carbon budget should different countries get) is orthogonal to the dynamic efficiency issue raised here. Our point is simply that if countries have different discount rates, insisting on equal marginal abatement cost throughout the upcoming decades of decarbonization is inefficient, because gains are on the table from re-allocating effort within countries *across* time.

References

Anthoff, D. and J. Emmerling (2019): "Inequality and the Social Cost of Carbon," *Journal of the Association of Environmental and Resource Economists*, 6, 29–59.

Anthoff, D. and R. S. Tol (2010): "On international equity weights and national decision making on climate change," *Journal of Environmental Economics and Management*, 60, 14–20.

Arrow, K. J., W. R. Cline, K.-G. Maler, M. Munasinghe, R. Squitieri, and J. E. Stiglitz (1996): *Intertemporal equity, discounting, and economic efficiency*, Cambridge, UK, New York and Melbourne: Cambridge University Press.

Banerjee, A. V. and E. Duflo (2005): "Chapter 7 Growth Theory through the Lens of Development Economics," in *Handbook of Economic Growth*, ed. by P. Aghion and S. N. Durlauf, Elsevier, vol. 1 of *Handbook of Economic Growth*, 473 – 552.

Bosetti, V., M. Tavoni, E. D. Cian, and A. Sgobbi (2009): "The 2008 WITCH Model: New Model Features and Baseline," Working Paper 2009.85, Fondazione Eni Enrico Mattei.

Bovenberg, A. L. and R. A. de Mooij (1994): "Environmental taxes and labor-market distortions," *European Journal of Political Economy*, 10, 655–683.

Bovenberg, A. L. and L. H. Goulder (1996): "Optimal Environmental Taxation in the Presence of Other Taxes: General-Equilibrium Analyses," *American Economic Review*, 86, 985–1000.

Caselli, F. and J. Feyrer (2007): "The marginal product of capital," *The quarterly journal of economics*, 122, 535–568.

Chari, V. V., P. J. Kehoe, and E. R. McGrattan (2007): "Business cycle accounting," *Econometrica*, 75, 781–836.

Chichilnisky, G. and G. Heal (1994): "Who should abate carbon emissions? : An international viewpoint," *Economics Letters*, 44, 443–449.

Dennig, F., M. B. Budolfson, M. Fleurbaey, A. Siebert, and R. H. Socolow (2015): "Inequality, climate impacts on the future poor, and carbon prices," *Proceedings of the National Academy of Sciences*, 112, 15827–15832.

Drupp, M. A., M. C. Freeman, B. Groom, and F. Nesje (2018): "Discounting Disentangled," *American Economic Journal: Economic Policy*, 10, 109–134.

Goulder, L. H. (2013): "Climate change policy's interactions with the tax system," *Energy Economics*, 40, S3–S11.

Gourinchas, P.-O. and O. Jeanne (2013): "Capital Flows to Developing Countries: The Allocation Puzzle," *The Review of Economic Studies*, 80, 1484–1515.

Hotelling, H. (1931): "The Economics of Exhaustible Resources," *Journal of Political Economy*, 39, 137–175.

Hsieh, C.-T. and P. J. Klenow (2007): "Relative prices and relative prosperity," *American Economic Review*, 97, 562–585.

Kemfert, C. and R. S. J. Tol (2002): "Equity, international trade and climate policy," *International Environmental Agreements*, 2, 23–48.

Lipsey, R. G. and K. Lancaster (1956): "The general theory of second best," *The review of economic studies*, 24, 11–32.

Monge-Naranjo, A., J. M. Sánchez, and R. Santaeulàlia-Llopis (2019): "Natural Resources and Global Misallocation," *American Economic Journal: Macroeconomics*, 11, 79–126.

Moore, F. C. and D. B. Diaz (2015): "Temperature impacts on economic growth warrant stringent mitigation policy," *Nature Climate Change*, 5, 127.

Negishi, T. (1960): "Welfare economics and existence of an equilibrium for a competitive economy," *Metroeconomica*, 12, 92–97.

Nordhaus, W. D. (2007): "A Review of the Stern Review on the Economics of Climate Change," *Journal of Economic Literature*, 45, 686–702.

Nordhaus, W. D. and Z. Yang (1996): "A Regional Dynamic General-Equilibrium Model of Alternative Climate-Change Strategies," *The American Economic Review*, 86, 741–765.

Parry, I. W. H. (1995): "Pollution Taxes and Revenue Recycling," *Journal of Environmental Economics and Management*, 29, S64–S77.

Ramsey, F. P. (1928): "A Mathematical Theory of Saving," *The Economic Journal*, 38, 543–559.

Reinhart, C. M. and K. S. Rogoff (2004): "Serial default and the" paradox" of rich-to-poor capital flows," *American Economic Review*, 94, 53–58.

Sandmo, A. (2007): "Global public economics: Public goods and externalities," *Économie publique/Public economics*.

Stern, N. (2006): *Stern Review: The Economics of Climate Change*, London: HM Treasury.