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Abstract

We derive the optimal contributions to global climate policy when countries differ with respect to income level and pollution intensity. Countries' growth rates are determined endogenously, and abatement efficiency is improved by technical progress. We show that country heterogeneity has a crucial impact on optimal policy contributions: more developed countries have to make a larger effort while less developed countries are allowed to graduate under a less stringent environmental regime. The optimal allocation of pollution permits depends on international trade. In the absence of international permit trade, more developed countries should receive more permits than the less developed countries but permit prices are higher in the rich countries. With international permit trade, more developed countries receive less permits than the less developed. When global distribution of physical capital is uneven and the aggregate pollution ceiling is low, poor countries receive all the permits and incomes do not converge, even with free trade.

Keywords: Climate policy, growth, abatement efficiency, policy convergence.
JEL Classification: *Q43, O47, Q56, O41*

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1 Introduction

How much should each country contribute to global climate policy? This is a consequential question in international climate negotiations but less a focus of standard economics. Economists are primarily concerned with efficiency and the objective of reaching internationally agreed temperature targets at minimal cost (Cramton et al. 2015). However, a policy assessment includes distributional issues, in particular in a world which is very heterogenous. Indeed, international climate negotiations have revealed significant differences in countries' negotiation positions, which are often related to the stage of development and the carbon intensity of the economy. Equity and fairness are prime concerns of climate negotiators and policy makers: the distribution of the burden of a global policy is central to them and their electorate. The implementation of stringent policies and further progress in international climate negotiations will thus depend on whether country contributions are perceived as both equitable and efficient.

It is known that in the presence of global pollution externalities, efficiency can be restored by implementing either a uniform global pollution price or a globally linked pollution permit market. But to derive the welfare impact of these policies on different countries, one has to also consider equity, which means specifying a distribution scheme for tax revenues (D'Autume et al. 2016), or an initial distribution pattern for pollution permits (Bretschger 2017). This especially applies for a policy affecting the economy significantly, as in the case for climate change. The welfare of countries is affected by pollution, but also by the impacts of environmental policy. It can be studied by adopting a macroeconomic setup with pollution externalities where country heterogeneities, such as the differences in pollution intensity, are taken into account. Moreover, as the stock of greenhouse gases and climate policies interact with the growth process in the economy, a dynamic perspective should be adopted. Finally, taking a world planner perspective allows the combination of the efficiency requirement with equity considerations because the planner aggregates over the countries' welfare (Chichilnisky and Heal 1994). Specifically, the utility functions of the different countries reflect the marginal valuations of consumer goods, which are typically related to income. Thus, a planner solution for a world with dynamic heterogeneous economies characterizes a global optimum, which can serve as a guideline for international environmental policy. This is where the present paper makes a contribution.

We derive optimal contributions of the countries to global climate policy in a model of endogenous growth with polluting capital. Countries are heterogenous with respect to income and pollution intensities; abatement technology is global due to international knowledge diffusion, like in the case of solar panels. Policy sets a ceiling to pollution stock and distributes pollution permits to the countries. We first use a simple one-country setting to develop the methodology. Then we apply the framework to multiple countries with different kinds of heterogeneities. We adopt a planner perspective to establish the global optimum and then show if and how the optimum can be replicated with a market solution and a specific initial distribution of pollution permits. The paper distinguishes the two cases with capital mobility and international permit trade and without capital mobility and international permit trade. Income differences and the growth pollution trade-off will be essential for the results. We find that more developed countries receive more permits than the less developed, but have to pay higher pollution prices in the case of no capital mobility and no international permit trade. Once we allow capital movement and free permit trade, more developed countries receive fewer permits than the less developed or even no permits at all. When global distribution of physical capital is uneven and the aggregate pollution ceiling is low incomes do not converge in the long run.

Our paper is related to different strands of literature. An early contribution deriving optimal carbon policies across countries is Chichilnisky and Heal (1994). They model the atmosphere as a public good and find that, for conventional utility functions and abatement provision, the social optimum implies lower levels of abatement in poor countries than in rich countries. They conclude that the requirement of international equalization of marginal abatement cost either ignores distributional issues or assumes unrestricted lump-sum transfers between the countries. D'Autume et al (2016) show that the world carbon price should be uniform, even in a second-best framework where public goods have to be financed through distortionary taxation and the cost of public funds has to be weighted against the utility of public goods. But this result only holds when lump-sum transfers between countries are possible without restriction. Conversely, if transfers between governments are not possible, international differentiation of the carbon price is the only way to take care of equity concerns. For the sectoral level, Hoel (1996) shows that a carbon tax should not be differentiated between polluting and non-polluting sectors when import and export tariffs are available for all goods. Like these contributions, we adopt an international setup but add the endogenous growth perspective and an analysis of the growth-pollution trade-off with environmental externalities.

By focusing on country contributions to global climate policy the paper is related to the analysis of equity principles in policy by Rose et al. (1998) and Konow (2003) and the applications to environmental economics in Grasso (2007), Page (2008) and Johansson-Stenman and Konow (2010). Specific rules for burden sharing in climate policy based on equity principles are derived and discussed in Lange et al. (2007), Mattoo and Subramanian (2010), and Bretschger (2013); egalitarian access to carbon space is proposed by Bode (2004) and BASIC (2011). We embed the equity topic in a social planner approach, start from first principles, and develop a full-fledged macroeconomic setup to derive optimal solutions for global climate policy. The dynamic aspects of climate change and climate policy are studied in Bretschger and Valente (2011), where country heterogeneity is introduced, and in Dietz and Venmans (2017) which derives optimal policies in the light of recent advances in climate sciences for the world economy.

Implementing effective global policies with heterogenous countries is the difficult task of international climate negotiations. If countries were purely selfish and short-sighted, policy costs would have to be distributed such that no single country would lose from an international climate treaty, following the notion of "international Paretianism" (Posner and Weisbach 2012). As a consequence, climate vulnerable and poor countries would have to compensate pollution intensive countries for decarbonization. However, this appears to violate the general perception of equity and fairness. Under these conditions it is very difficult to reach an effective global climate agreement. But in reality, additional forces like coalition formation, positive externalities from technologies and policies, and extrinsic motivation of negotiators also play a role (Bretschger 2017). In terms of instrument choice for climate policy, Weitzman (2014), Stiglitz (2015) and Cramton et al. (2015) favor a world uniform carbon tax which is a clear one-dimensional target, facilitating negotiations and preventing free riding on other countries' efforts. Conversely, a pollution quota and the international distribution of pollution permits need to be negotiated in a more complex manner but address the countries' equity concerns in a direct way. From the perspective of political economy, McKenzie and Ohndorf (2012) argue that revenue-raising instruments, such as carbon taxes are suboptimal because they give rise to unproductive rent seeking, which is avoided with freely allocated permits. We will solve our model formally for the international allocation of pollution permits but could easily reinterpret our results in terms of carbon taxes with international redistribution of tax revenues. We will compare the case of no capital movement and no permit trade with the regime of free capital movement and full permit trade and derive the consequences for the different countries. This complements the findings of Böhringer et al. (2014) who find that pollution intensive economies generally have conflicting interests with less polluting countries about admitting more countries to a permit trading coalition.

The remainder of the paper is organized as follows. Section 2 develops the general setup for the social optimum and the decentralized equilibrium. In Section 3, we introduce multiple heterogenous countries. Section 4 analyses the impact of capital and permit trade. In Section 5 we discuss optimal policies and Section 6 concludes.

2 General Setup

We first develop and solve the model for a single economy which may be thought of as either a single country or the world economy. Applications of the framework to multiple heterogenous countries are made in subsequent sections, where we distinguish the cases without and with international trade and add the conclusions for optimal policies.

2.1 Social Optimum

We consider an economy in which output is produced by using capital k with a linear technology (Rebelo 1991) represented by factor productivity $A > 0$. Capital use is polluting. The impact on emissions is given by pollution intensity $\nu > 0$; abatement efficiency grows due to technical progress in cleaning processes at a rate $1/\gamma$, where $0 < \gamma \leq 1$. If at time t the capital stock is k_t, the level emissions is equal to $\gamma^t \nu k_t$, where γ^t is the t-th degree of γ, and the output is Ak_t. Output can be used for consumption c_t or for building future capital stock k_{t+1}. The representative consumer maximizes intertemporal utility with a log felicity function and a discount factor β. We assume that

$$\gamma A > 1, \quad \beta A > 1.$$

The social planner limits emissions, aggregated over all time periods, to $E_0 > 0$. Thus, given the initial stock of capital, $k_0 = \hat{k}_0 > 0$, the social planner solves the program

$$\max \sum_{t=0}^{\infty} \beta^t \ln c_t \tag{1}$$

$$k_{t+1} + c_t = Ak_t, \ t = 0, 1, ... \quad (p_t) \tag{2}$$

$$\sum_{t=0}^{\infty} \gamma^t \nu k_t \leq E_0. \quad (q) \tag{3}$$

Here and below in parentheses we indicate the Lagrange multipliers associated with the corresponding constraints. The first-order conditions of this problem are given by

$$p_t = \frac{\beta^t}{c_t}, \ t = 0, 1, ..., \tag{4}$$

$$Ap_t = p_{t-1} + \gamma^t \nu q \tag{5}$$

and the solution is, see Appendix A,

$$\frac{1}{c_t} = \frac{1}{\beta^t A^t}\left[\frac{1}{c_0} + \nu\gamma q \frac{1-\gamma^t A^t}{1-\gamma A}\right],\ t = 0, 1, ... \tag{6}$$

which implies that

$$\frac{c_{t+1}}{c_t} \xrightarrow[t\to\infty]{} \frac{\beta}{\gamma}. \tag{7}$$

In Appendix A we also prove that

$$\frac{k_{t+1}}{c_t} \xrightarrow[t\to\infty]{} \frac{\beta}{\gamma A - \beta} \tag{8}$$

and hence

$$\frac{k_{t+1}}{k_t} \xrightarrow[t\to\infty]{} \frac{\beta}{\gamma}. \tag{9}$$

From (7) and (9) we see that the long-run growth rate of the economy does not depend on total factor productivity A, as could have been expected from an endogenous growth perspective. It is rather determined by the impatience of households (β) and the development of the cleaning technology (γ), which reveals the dominant impact of the aggregate pollution restriction E_0 in this economy.

2.2 Decentralized Equilibrium

To enforce pollution restrictions in the decentralized equilibrium, the government allocates a pollution quota in the form of permits to households equal to the amount of E_0. Like capital, the permits are individual assets; they are freely tradable on permit markets. Aggregate pollution quantity is fixed like the stock of an exhaustible resource; hence, in an intertemporal setup, pollution permit prices have characteristics similar to exhaustible resource prices, reflecting increasing scarcity over time.

We denote by s_t the savings, by $1 + r_t$ the gross interest rate in period t, and by π_t the price of pollution at (the end of) period t. The representative consumer solves the program

$$\max \sum_{t=0}^{\infty} \beta^t \ln c_t \tag{10}$$

$$c_0 + s_0 = Ak_0 + \pi_0 E_0, \tag{11}$$

$$c_t + s_t = (1 + r_t)s_{t-1},\ t = 1, 2, ... \tag{12}$$

$$\lim_{T\to\infty} \frac{s_T}{\Pi_{t=1}^T (1 + r_t)} \geq 0 \tag{13}$$

Its solution is given by

$$\begin{cases} c_0 = (1-\beta)(Ak_0 + \pi_0 E_0),\ s_0 = \beta(Ak_0 + \pi_0 E_0), \\ c_t = (1-\beta)(1+r_t)s_{t-1},\ s_t = \beta(1+r_t)s_{t-1}, \qquad t = 1, 2, ... \end{cases} \tag{14}$$

Equilibrium in the decentralized case is defined by two conditions for financial and for goods markets. In the financial market equilibrium, savings are distributed between physical capital and the pollution quotas of the next period according to

$$s_t = k_{t+1} + \pi_t \gamma^{t+1} \nu k_{t+1} + \pi_t E_{t+1}, \ t = 0, 1, ..., \tag{15}$$

where E_{t+1} is the total quantity of pollution permits at the beginning of period $t+1$, while in the goods markets we still have the equilibrium

$$c_t + k_{t+1} = Ak_t, \ t = 0, 1, ... \tag{16}$$

The return to savings (i.e. the interest rate), r_{t+1}, is determined by

$$(1 + r_{t+1})s_t = Ak_{t+1} + \pi_{t+1}E_{t+1}, \ t = 0, 1, ... \tag{17}$$

For the price of pollution permits we obtain

$$1 + r_{t+1} = \frac{\pi_{t+1}}{\pi_t}, \ t = 0, 1, ... \tag{18}$$

which corresponds to the Hotelling rule known from exhaustible resources when we abstract from extraction costs (Hotelling 1931).

Proposition 1. *The decentralized equilibrium with optimum pollution quantities and free pollution permit trade replicates the social optimum.*

Proof. It is sufficient to note that the equilibrium (current value) price of pollution in decentralized equilibrium is given by

$$\pi_t = \frac{q}{p_t}, \ t = 0, 1, ...,$$

which reflects the pollution valuation in social optimum. □

To further characterize the properties of the decentralized equilibrium we state and prove the following proposition.

Proposition 2. *For sufficiently low values of E_0 (such that the pollution constraint is binding and hence q and π_t, $t = 0, 1, ...,$ are positive), the price of pollution permits π_t and the total value of permits, $\pi_t E_t$ are decreasing and the interest rate $1 + r_t$ are increasing in E_0 for each $t = 0, 1, ...$*

Proof. See Appendix B. □

That prices of pollution permits and the aggregate value of permits are decreasing in total pollution quantity confirms the stringent effects of environmental policy in our dynamic setting. Note that in equilibrium, the dynamics of the price of pollution permits is given by

$$\pi_{t+1} = \frac{A\pi_t}{1 + \pi_t \gamma^{t+1} \nu}, \ t = 0, 1, ... \tag{19}$$

and the relationship between the interest rate and the price of pollution permits becomes

$$1 + r_{t+1} = \frac{A}{1 + \pi_t \gamma^{t+1} \nu}, \ t = 0, 1, ... \quad . \tag{20}$$

We see that the interest rate is decreasing in pollution price so that, based on the previous finding, it is growing with admitted pollution quantity. Note also that the natural balance of pollution permits holds true in equilibrium:

$$\gamma^{t+1} \nu k_{t+1} + E_{t+1} = E_t, \ t = 0, 1, ... \tag{21}$$

Next we apply the model setup to the multicountry case to derive optimal policies in a heterogeneous world.

3 Many countries

3.1 Social Optimum

We consider n different countries and seek for a Pareto optimum, given a global pollution constraint as in the example of climate policy. Neither international permit trade nor capital movement is included in this section, they will be treated separately in the next section. We denote by $\lambda^i > 0$ the Pareto weight of country i ($\sum_{i=1}^n \lambda^i = 1$) in the aggregate welfare. It is natural to assume that λ^i reflects country i's population size but one may also apply additional criteria.[3] In each time period t and in each country i, the flow of emissions e_t^i is proportional to the stock of capital k_t^i with the coefficient of proportionality $\gamma^t \nu^i$, where γ^t is common for all countries and ν^i is specific for country i:

$$e_t^i = \gamma^t \nu^i k_t^i,$$

while world emissions in year t are

$$e_t = \sum_{i=1}^n e_t^i.$$

[3] Konow (2003) and Bretschger (2013) discuss equity principles such as the ability to pay or the merit principle in this context.

Technology γ^t is assumed to be globally available due to international knowledge diffusion. If $\gamma < 1$, then in all countries, the emissions-to-capital ratio decreases over time to ultimately approximate zero, due to technical progress in abatement.

We impose the constraint that, at any time, the stock of pollution cannot exceed E_0

$$\sum_{t=0}^{\infty} e_t \leq E_0,$$

or, equivalently,

$$\sum_{t=0}^{\infty} \gamma^t \sum_{i=1}^{n} \nu^i k_t^i \leq E_0.$$

Let the initial stock of capital in each country $i = 1, ..., n$, $k_0^i = \hat{k}_0^i > 0$ be given. We want to solve the program

$$\max \sum_{j=1}^{n} \lambda^i \sum_{t=0}^{\infty} \beta^t \ln c_t^i \tag{22}$$

$$k_{t+1}^i + c_t^i = Ak_t^i, \ t = 0, 1, ... \quad (\tilde{p}_t^i) \tag{23}$$

$$\sum_{t=1}^{\infty} \gamma^t \sum_{i=1}^{n} \nu^i k_t^i \leq E \qquad (\tilde{q}) \tag{24}$$

which, compared to the previous section, includes n different countries. In the following we use $E_0^i = \sum_{t=0}^{\infty} e_t^i$ for the total emissions of country i. Clearly, $\sum_{i=1}^{n} E_0^i = E_0$. For the comparison of different countries we use exemplary country labels i and j. Solving the problem given in (22)-(24) yields the result summarized in the following proposition.

Proposition 3. *In the social optimum with n different countries and in the absence of capital mobility and international permit trade*

1. *the rate of growth in each country converges to the ratio β/γ:*

$$\lim_{t\to\infty} \frac{k_{t+1}^i}{k_t^i} = \lim_{t\to\infty} \frac{c_{t+1}^i}{c_t^i} = \frac{\beta}{\gamma}, \ i = 1, ..., n; \tag{25}$$

2. *the ratio of emissions between two countries converge to the ratio of the Pareto weights, irrespective of the countries' pollution intensities:*

$$\lim_{t\to\infty} \frac{e_t^i}{e_t^j} = \frac{\lambda^i}{\lambda^j}, \ i, j = 1, ..., n; \tag{26}$$

3. *if initially country i is less polluting than country j, then the savings and growth rates of country i will be higher than in country j:*

$$\frac{\nu^i}{\lambda^i} k_0^i = \frac{e_0^i}{\lambda^i} < \frac{e_0^j}{\lambda^j} = \frac{\nu^j}{\lambda^j} k_0^j$$
$$\Rightarrow \frac{k_{t+1}^i}{Ak_t^i} > \frac{k_{t+1}^j}{Ak_t^j} \ \textit{and} \ \frac{e_{t+1}^i}{e_t^i} > \frac{e_{t+1}^j}{e_t^j}, \ i, j = 1, ..., n, \ t = 0, 1, 2, ...; \tag{27}$$

4. if initially country i is less polluting than country j, then the optimal amount of pollution permits given to country i is less than the amount given to country j:

$$\frac{\nu^i}{\lambda^i}k_0^i = \frac{e_0^i}{\lambda^i} < \frac{e_0^j}{\lambda^j} = \frac{\nu^j}{\lambda^j}k_0^j \Rightarrow \frac{E_0^i}{\lambda^i} < \frac{E_0^j}{\lambda^j}, \ i, j = 1, ..., n. \tag{28}$$

Proof. See Appendix C. □

The first statement of the proposition concerning countries' long-run growth rates looks familiar from the previous section while the second one (convergence of the proportion of emissions between countries) reveals the dynamic adjustment process through capital accumulation. Here it is noteworthy that (26) implies that the ratio of consumption and the ratio of capital stocks in two countries converge to the ratio of Pareto weights normalized by pollution intensities:

$$\lim_{t\to\infty} \frac{c_t^i}{c_t^j} = \lim_{t\to\infty} \frac{k_t^i}{k_t^j} = \frac{\lambda^i/\nu^i}{\lambda^j/\nu^j}, \ i, j = 1, ..., n \tag{29}$$

Concerning the third and fourth statements of the proposition, note that initially country i can be less polluting than country j ($e_0^i/\lambda^i < e_0^j/\lambda^j$) either because i is less developed than j ($k_0^i/\lambda^i < k_0^j/\lambda^j$) or because the pollution intensity of i is lower than that of j ($\nu^i < \nu^j$). Though the fourth statement says that the total amount of pollution permits given to more polluting country is higher than that given to less polluting one, this does not mean that the pollution permits are given proportionally to the initial emissions. It follows from (27) that the ratio of pollution permits to initial emissions is higher in less polluting countries:

$$\frac{e_0^i}{\lambda^i} < \frac{e_0^j}{\lambda^j} \Rightarrow \frac{E_0^i}{e_0^i} > \frac{E_0^j}{e_0^j}, \ i, j = 1, ..., n.$$

The fourth statement of the proposition also implies that efficient contributions to climate policy are unequal between countries, i.e. an optimal distribution of permits partially accommodates the higher demand for permits of more polluting countries to fulfill the policy targets. As we will see shortly it does not mean that optimal pollution prices are internationally equalized.

3.2 Decentralization Equilibrium

Knowing the optimal values of $e_t^i = \gamma^t \nu^i k_t^i$, at time 0 we allocate to each country i

$$E_0^i = \sum_{t=1}^{\infty} e_t^i$$

units of pollution quota and let the representative consumer in each country solve her optimization problem according to

$$\max \sum_{t=0}^{\infty} \beta^t \ln c_t^i \tag{30}$$

$$k_{t+1}^i + c_t^i = Ak_t^i,\ t = 0, 1, ... \quad (\hat{p}_t^i) \tag{31}$$

$$\sum_{t=1}^{\infty} \gamma^t \nu^i k_t^i \leq E_0^i \qquad (\hat{q}^i) \tag{32}$$

It is not difficult to verify that

$$\hat{q}^i = \frac{\tilde{q}^i}{\lambda^i} \text{ and } \hat{p}_t^i = \frac{\tilde{p}_t}{\lambda^i},\ i = 1, ..., n,\ t = 0, 1, ... \tag{33}$$

Based on Proposition 2, the solution of this problem can indeed be decentralized in each country separately. Then, in country i the price of pollution is given by

$$\pi_t^i = \frac{\hat{q}^i}{\hat{p}_t^i} = \frac{\tilde{q}}{\tilde{p}_t},\ t = 0, 1, ..., \tag{34}$$

the gross interest rate is

$$1 + r_{t+1}^i = \frac{A}{1 + \pi_t^i \gamma^{t+1} \nu^i},\ t = 0, 1, ..., \tag{35}$$

and the dynamics of the price of pollution read

$$\pi_t^i = \frac{A\pi_{t-1}^i}{1 + \pi_{t-1}^i \gamma^t \nu^i},\ t = 0, 1, ... \tag{36}$$

Since now the pollution price becomes

$$\pi_t^i = \frac{\tilde{q} c_t^i}{\lambda^i \beta^t},\ i, j = 1, ..., n,\ t = 0, 1, ..., \tag{37}$$

we have

$$\pi_t^i > \pi_t^j \ \Leftrightarrow\ \frac{c_t^i}{\lambda^i} > \frac{c_t^j}{\lambda^j},\ i, j = 1, ..., n,\ t = 0, 1, ..., \tag{38}$$

which implies that, after correcting for the Pareto weights, in a richer country the price of pollution is higher. Also we have

$$1 + r_{t+1}^i > 1 + r_{t+1}^j \ \Leftrightarrow\ \nu^i \pi_t^i < \nu^j \pi_t^j,\ i, j = 1, ..., n,\ t = 0, 1, ... \tag{39}$$

This reflects that after normalization of the pollution intensity, the interest rate is lower in a richer country.

These findings have crucial implications for optimal policy contributions: More advanced economies are given an optimal pollution quota such that the resulting permit price is higher than in less developed countries. Permit prices are the most prominent signal for the stringency of environmental policy. Thus, following our global optimality criterion, more developed countries have to make a higher contribution to solving the environmental problem, while less developed countries are allowed to graduate under a less stringent environmental regime. So far, this holds in the absence of capital movement and trade. Indeed, when we allow capital mobility and open the economies for permit trade in the next section, permit prices will equalize. But importantly, there will also be income transferred from rich to poor economies in exchange for the purchase of permits. Whether free permit trade will ultimately be realized on a global level is also a political question: standard economics strongly advocates in favor because of the involved efficiency gains stemming from a decrease in aggregate abatement costs.

In terms of growth, we also see from (29)

$$\lim_{t\to\infty}\frac{\pi_t^i}{\pi_t^j}=\frac{1/\nu^i}{1/\nu^j} \text{ and } \lim_{t\to\infty}\frac{1+r_t^i}{1+r_t^j}=1,\ i,j=1,...,n. \tag{40}$$

saying that, in the long run, the interest rates between the countries converge, even without international capital trade, and the ratio of pollution prices between two countries i and j converges to the inverse ratio of pollution intensities.

4 Capital Mobility and International Permit Trade

4.1 Pareto Optimum

We now introduce the international exchange of capital and pollution permits. To focus on the effect of different income levels we assume from now on that the pollution intensity is the same in all countries: $\nu^i=\nu,\ i=1,...,n$. First we focus on the role of free capital transfers, which we add to our multicountry setup.

Let the initial stock of capital in each country $i=1,...,n$, $\hat{k}_0^i>0$ be given. Then, the program we consider becomes

$$\max\sum_{j=1}^{n}\lambda^i\sum_{t=0}^{\infty}\beta^t\ln c_t^i \tag{41}$$

$$\sum_{j=1}^{n}k_0^i=\sum_{j=1}^{n}\hat{k}_0^i, \tag{42}$$

$$\sum_{j=1}^{n}k_{t+1}^i+\sum_{j=1}^{n}c_t^i=\sum_{j=1}^{n}Ak_t^i,\ t=0,1,..., \tag{43}$$

$$\sum_{t=0}^{\infty}\gamma^t\sum_{i=1}^{n}\nu k_t^i\leq E_0 \tag{44}$$

To describe the solutions to this program, consider the maximization problem (1)-(3) with $k_0 = \sum_{j=1}^{n} \hat{k}_0^i$. It is easy to show that if $(c_t, k_{t+1})_{t=0}^{\infty}$ is the solution to (1)-(3), then one of the solutions to (41)-(44) is determined as follows:

$$c_t^i = \lambda^i c_t,\ k_t^i = \lambda^i k_t,\ i = 1, ..., n,\ t = 0, 1, 2, ... \tag{45}$$

What is important here is that the socially optimal proportion of the consumption of country i in the world consumption is equal to its Pareto weight λ_i. As for the capital stocks, it is clear that if, for any t, we replace the equalities $k_t^i = \lambda^i k_t$ $i = 1, ..., n$, by the condition that $\sum_{i=1}^{n} k_t^i = k_t$, we will also obtain a social optimum.

An optimal outcome will be obtained if we redistribute the initial stock of capital, $k_0 = \sum_{j=1}^{n} \hat{k}_0^i$, and the initial amount of permits, E_0, between countries in proportion to their Pareto weights ($k_0^i = \lambda^i \sum_{j=1}^{n} \hat{k}_0^i$ and $E_0^i = \lambda^i E_0$) and allow consumers in each country i to solve their own program

$$\max \sum_{t=0}^{\infty} \beta^t \ln c_t^i \tag{46}$$

$$k_1^i + c_0^i = Ak_0^i,\ k_{t+1}^i + c_t^i = Ak_t^i,\ t = 1, 2, ... \tag{47}$$

$$\sum_{t=0}^{\infty} \gamma^t \nu k_t^i \leq E_0^i. \tag{48}$$

4.2 Decentralized Equilibrium

In this subsection we allow international capital mobility and introduce pollution permits which can be traded freely between the countries. Similar to the analysis in the previous sections we ask whether it is possible to replicate the optimal solution to the program given in (41)-(44) in the decentralized case. Following the last subsection it is straightforward to state that the answer would be yes, provided we could freely distribute the pollution permits and, in addition, redistribute the initial capital stocks. Then, optimality conditions could easily be arranged. But, of course, in the real world it is not possible to redistribute capital stocks, so the plan is not compatible with the concept of the decentralized approach. Also, given our linear AK technology, there is *a priori* no incentive for market participants to transfer capital from rich to poor economies. Thus, the realistic question is whether it is possible to decentralize the optimal solution of (41)-(44) if we can freely distribute the pollution permits but cannot redistribute the initial capital stocks. In terms of climate policy contributions we can then also answer the question how such an efficient allocation of pollution permits would look like.

Suppose we are given a feasible redistribution of the initial world capital stock $(k_0^i)_{i=1}^n$ $(\sum_{j=1}^n k_0^i = \sum_{j=1}^n \hat{k}_0^i)$ and a feasible distribution of pollution permits, $(E_0^i)_{i=1}^n$ $(\sum_{i=1}^n E_0^i = E_0)$. Pollution permits are internationally tradable. We again denote by $1+r_t$ the (gross) interest rate in period t and by π_t the (world) price of pollution at (the end of) period t. The representative consumer in each country $i = 1, ..., n$ then solves:

$$\max \sum_{t=0}^{\infty} \beta^t \ln c_t^i \tag{49}$$

$$c_0^i + s_0^i = Y^i, \tag{50}$$

$$c_t^i + s_t^i = (1 + r_t)s_{t-1}^i, \ t = 1, 2, ... \tag{51}$$

$$\lim_{T\to\infty} \frac{s_T^i}{\Pi_{t=1}^T (1 + r_t)} \geq 0, \tag{52}$$

where

$$Y^i = Ak_0^i + \pi_0 E_0^i.$$

This program is similar to the consumer problem in Section 2. Note however, that we have now added country labels i for consumption, savings, capital stocks, and emission quantities. The solution to this program is

$$\begin{cases} c_0^i = (1-\beta)(Ak_0^i + \pi_0 E_0^i), \ s_0^i = \beta(Ak_0^i + \pi_0 E_0^i), \\ c_t^i = (1-\beta)(1+r_t)s_{t-1}^i, \ s_t^i = \beta(1+r_t)s_{t-1}^i, \qquad t = 1, 2, ... \end{cases} \tag{53}$$

Equilibrium is again defined by the conditions for financial and goods markets. In an equilibrium on the financial market, savings are distributed between physical capital and pollution quotas as follows

$$s_t^i = k_{t+1}^i + \pi_t \gamma^{t+1} \nu k_{t+1}^i + \pi_t E_{t+1}^i, \ i = 1, ..., n, \quad t = 0, 1, ..., \tag{54}$$

while equilibrium in the goods market now requires

$$\sum_{i=1}^n c_t^i + \sum_{i=1}^n k_{t+1}^i = \sum_{i=1}^n Ak_t^i, \ t = 0, 1, ... \tag{55}$$

The return to savings (interest rate), r_{t+1}, is given by

$$(1 + r_{t+1})s_t^i = Ak_{t+1}^i + \pi_{t+1} E_{t+1}^i, \ i = 1, ..., n, \quad t = 0, 1, ..., \tag{56}$$

where E_{t+1}^i is the quantity of pollution permits owned by country i at (the beginning of) period $t+1$, and again the Hotelling rule holds true

$$1 + r_{t+1} = \frac{\pi_{t+1}}{\pi_t}, \ t = 0, 1, ... \tag{57}$$

It is easy to check that in equilibrium, the dynamics of the pollution price are given by

$$\pi_{t+1} = \frac{A\pi_t}{1 + \pi_t \gamma^{t+1} \nu}, \ t = 0, 1, ..., \tag{58}$$

just like in the single country case and that the relationship between the interest rate and the price of pollution is again

$$1 + r_{t+1} = \frac{A}{1 + \pi_t \gamma^{t+1} \nu}, \ t = 0, 1, ... \tag{59}$$

In contrast to Section 2 we now have to consider aggregate emissions on a world level, so that the balance of pollution permits reads

$$\gamma^{t+1} \nu \sum_{i=1}^{n} k_{t+1}^i + \sum_{i=1}^{n} E_{t+1}^i = \sum_{i=1}^{n} E_t^i, \ t = 0, 1, ... \tag{60}$$

It should be highlighted that the exact proportion in which the savings of country i at time t, s_t^i, are divided between physical capital k_{t+1}^i and pollution quotas $\pi_t \gamma^{t+1} \nu k_{t+1}^i + \pi_t E_{t+1}^i$ is indeterminate (and irrelevant) in equilibrium.

Proposition 4. *Suppose we are given an initial world stock of capital, $\sum_{j=1}^n \hat{k}_0^i > 0$, and a world emission quota $E_0 > 0$. In a decentralized equilibrium, the equilibrium prices of pollution, π_t, $t = 0, 1, 2, ...$, and the interest rates, $1 + r_{t+1}$ $t = 0, 1, 2, ...$, do not depend on the initial distribution of the capital stock, $(k_0^i)_{i=1}^n$, and the emission quota, $(E_0^i)_{i=1}^n$, among the countries.*

Proof. It is sufficient to note that the equilibrium prices of pollution, π_t, $t = 0, 1, 2, ...$, are given by

$$\pi_t = \frac{q}{p_t}, \ t = 0, 1, 2, ... \tag{61}$$

where p_t and q are the Lagrange multipliers of problem (1)-(3) at $k_0 = \sum_{j=1}^n \hat{k}_0^i$, which depend on the initial world stock of capital, $k_0 > 0$, and the world emission quota $E_0 > 0$, but do not depend on their distribution among the countries. $\square$

The property that the equilibrium prices of pollution, π_t, and the interest rate, $1+r_{t+1}$, do not depend on the initial distribution of the pollution permits, constitutes a modern application and verification of the famous Coase theorem.

The consumption stream of the representative consumer in country i in equilibrium depends on its initial stock of capital and permit. More specifically,

$$c_0^i = (1 - \beta) Y^i, \ c_2^i = (1 - \beta) \beta^t (1 + r_2)(1 + r_1) Y^i, \ ...,$$
$$c_t^i = (1 - \beta) \beta^t (1 + r_t) ... (1 + r_1) Y^i, ... \tag{62}$$

Therefore, in equilibrium, the ratio of country i's to country j's consumption does not change over time and equals the ratio of country i's to country j's initial wealth

$$\frac{c_0^i}{c_0^j} = \frac{c_1^i}{c_1^j} = ... = \frac{c_t^i}{c_t^j} = ... = \frac{Y^i}{Y^j}, \; i, j = 1, ..., n. \tag{63}$$

Also it follows from (62) that the utility of the representative consumer in country i is

$$\begin{aligned}\sum_{t=0}^{\infty} \beta^t \ln c_t^i &= \sum_{t=0}^{\infty} \beta^t \ln(1-\beta) + \sum_{t=1}^{\infty} \beta^t \ln \beta \\ &+ \sum_{t=1}^{\infty} \beta^t \ln(1+r_1) + \sum_{t=2}^{\infty} \beta^t \ln(1+r_2) + ... + \sum_{t=0}^{\infty} \beta^t \ln Y^i \\ &= \frac{1}{1-\beta} \ln(1-\beta) + \frac{1}{1-\beta} \ln \beta + \sum_{t=1}^{\infty} \beta^t (1+r_t) + \frac{1}{1-\beta} \ln Y^i,\end{aligned}$$

and hence the world welfare is

$$\sum_{j=1}^{n} \lambda^i \sum_{t=0}^{\infty} \beta^t \ln c_t^i = \frac{1}{1-\beta} \ln(1-\beta) + \frac{1}{1-\beta} \ln \beta + \sum_{t=1}^{\infty} \beta^t (1+r_t) + \frac{1}{1-\beta} \sum_{i=1}^{n} \lambda^i \ln Y^i.$$

Thus, to maximize the world welfare in equilibrium by means of redistributing the initial world stock of capital and distributing the world emission quota, it is necessary (and sufficient) to solve the following problem:

$$\max \sum_{i=1}^{n} \lambda^i \ln Y^i, \tag{64}$$

$$\sum_{i=1}^{n} Y^i = \sum_{i=1}^{n} A\hat{k}_0^i + \pi_0 E_0. \tag{65}$$

The solution to this problem is given by

$$Y^i = \lambda_i \left(\sum_{i=1}^{n} A\hat{k}_0^i + \pi_0 E_0 \right), \; i = 1, ..., n. \tag{66}$$

It is easy to check that if the initial redistribution of the world stock of capital and distribution of emission quota are such that (66) is satisfied, the world welfare in equilibrium is equal to the optimal value to the world welfare optimization problem (41)-(44). In this sense the world social optimum can be decentralized. However, such a decentralization is based on the assumption that we can redistribute the initial world stock of capital. This assumption is unrealistic.

Is it possible to decentralize the world social optimum if redistributing the initial world stock of capital is impossible, but we are free to distribute the world emission quota? The answer to this question is given by the following proposition.

Proposition 5. *Suppose that redistributing the initial world stock of capital is impossible.*

Then in the case where

$$\lambda_i \left(\sum_{i=1}^{n} A\hat{k}_0^i + \pi_0 E_0 \right) \geq A\hat{k}_0^i, \ i = 1, ..., n, \tag{67}$$

there is a distribution of initial permits E_0 among the countries such that the world welfare in equilibrium is equal to the optimal value of problem (41)-(44), i.e. the world social optimum can be fully decentralized.

Otherwise for any distribution of E_0 among the countries the world welfare in equilibrium is lower than the optimal value of problem (41)-(44), i.e. the world social optimum can not be decentralized.

Proof. When redistributing the initial world stock of capital is impossible, to maximize the world social welfare we should solve the following maximization problem:

$$\max \sum_{i=1}^{n} \lambda^i \ln Y^i, \tag{68}$$

$$\sum_{i=1}^{n} Y^i = \sum_{i=1}^{n} A\hat{k}_0^i + \pi_0 E_0, \tag{69}$$

$$Y^i \geq A\hat{k}_0^i, \ i = 1, ..., n. \tag{70}$$

It is clear that if (67) is satisfied, then the solution and optimal value to this problem are the same as the solution optimal value of problem (64)-(65); otherwise its optimal value is lower than that of (64)-(65). □

It should be noted that for a sufficiently large E_0 the emission constraint (44) is not binding and hence $\pi_0 = 0$. For smaller values of E_0 the emission constraint is binding and $\pi_0 E_0$ is decreasing in E_0. It follows that the optimal solution to problem (41)-(44) can be fully decentralized if the initial distribution of physical capital is not too uneven and the world amount of pollution permits is rather small.

To implement the decentralization, it is necessary to give less developed countries more permits in order to obtain a distribution of the world wealth satisfying

$$Ak_0^i + \pi_0 E_0^i = \lambda^i \left(\sum_{i=1}^{n} A\hat{k}_0^i + \pi_0 E_0 \right), \ i = 1, ..., n. \tag{71}$$

which would equalize *per capita* wealth of all countries. This may be seen as a quite radical requirement but it follows directly from our global social optimum with equal treatment of all people in the world (if we interpret λ^i as the share of i-th country in the world population).

Empirics show that the aggregate capital stock is highly concentrated on a global level. In our model, an optimal distribution of world wealth is impossible if the initial distribution of physical capital is very uneven and/or the initial value of the world emission quota, $\pi_0 E_0$, is small. In this case all permits will be given to less developed countries, while the most developed countries will not receive any allowances. This conclusion is similar to the notion of an "egalitarian access to carbon space" but is derived from a dynamic economic model as an efficient policy. We summarize and further characterize our findings in the next section.

Finally, note that when the world social optimum can be decentralized, the optimal equilibrium is characterized by full *per capita* consumption equality among the countries (again if λ^i is the share of i-th country in the world population). Otherwise, *per capita* consumption in equilibrium will be unequal forever (see (63)).

5 Optimal Policies

We are now ready to discuss our main results in the light of the starting point, the efficient and equitable contribution of countries to international climate policy and their impacts. We will distinguish the different cases treated in the paper.

5.1 Optimal Permit Distribution

When global climate policy is based on permit markets, the allocation of pollution permits to countries is a central issue. We have found that if there is no international capital movement and permits are not traded internationally, it is optimal on a global to give *ceteris paribus* more permits to more developed countries, see (28). If, however, capital moves freely and international permit trade becomes possible, the situation is just the opposite: more developed countries receive fewer permits in an optimal distribution. It is then optimal from a global perspective that these countries acquire additional permits via the international market.

We conclude that the decision on an optimal international distribution of permits depends on a question of institutional arrangement, which is whether national permit markets can be linked on a global level or not. This is a highly political issue. Economists would in general favor such a linking for efficiency reasons, but from a political perspective there might be reservations because countries then become interdependent in a crucial policy area.

5.2 Permit Prices

The prices of pollution permits are the main signal for the stringency of climate policy in a country. We find that in the absence of capital mobility and international permit trade, the equilibrium prices of pollution permits are higher in the rich countries than in the poor countries. This reflects the intense scarcity of pollution rights in developed regions which turns out to be optimal for policy burden sharing on a global level. Compared to the proposal of a uniform world carbon price, where countries keep their tax revenues, we see that developed countries are requested to pay more, given the global optimization.

Of course, as soon as capital moves freely and permits become tradable at the international level, pollution permit prices immediately equalize. This is in the mutual interest of buyers and sellers of permits; a standard result of environmental economics, which is equivalent to the proposal to establish uniform international carbon prices. But the decisive result here is that the optimal allocation of permits to richer countries is such that they induce an income transfer from the rich to the poorer countries with permit trade. Hence we have established that it is optimal to allocate a relatively higher burden of climate policy to the richer countries, provided we take a global welfare perspective as adopted in this paper.

5.3 Income convergence

If there is no international permit trade, countries' income levels converge, even if we observe no international capital movement. Pollution restrictions are strong enough to bring about convergence, which is a remarkable result.

If capital movement is allowed and permits are traded internationally, two scenarios are possible:

- If the initial distribution of physical capital is not too uneven and the world amount of pollution permits is small, i.e. when (67) holds true, then the distribution of the permits is such that all countries are in identical income positions from the first period on, which is a stable condition over time.
- If the initial distribution of physical capital is uneven and the world amount of pollution permits is not very small, i.e. if (67) does not hold, then complete equality between countries is not reached through the distribution of permits and moreover, the countries do not converge in the long run. This happens even when markets are fully globalized.

It is realistic to assume that the world economy is characterized by an uneven distribution of physical capital, but that international climate policy prescribes an aggregate amount of pollution permits which is quite small. Hence, the question of income convergence cannot be answered unambiguously. Global pollution restrictions entail convergence forces, but whether incomes ultimately converge depends on the stringency of the implemented environmental policy.

6 Conclusions

Using a multicountry endogenous growth model, we have derived optimal country contributions to international climate policies, which we defined as a cap on global pollution stock. We have found that an optimal policy design typically deviates from identical policy efforts of all the countries. In the adopted world planner approach, efforts are not equalized in absolute terms but in terms of marginal utilities. When capital does not move across national borders and permits are not traded internationally it means that more developed countries have to pay higher pollution prices despite the fact that they receive more pollution permits as an initial endowment. With free capital movement and international permit trade, pollution prices become uniform, more developed countries receive fewer permits in the beginning and marginal abatement costs are equalized internationally.

Our planner approach provides a theoretical guideline for optimal global policies. The international climate negotiations have the difficult task of inducing implementation of such policies in practice. If not in a precise manner and not all at once, the policy steps should at least point in the right direction i.e. move the economies from today's suboptimal state towards a global optimum. In the current climate policy process, instrument choice is delegated to the country level, where not only taxes and permits but also bans and other legal instruments play an important role. All these measures are especially effective when they induce further technical progress in abatement, which would be a possible extension of our approach. Also, the effects of the introduction of a second type of capital which is clean would be interesting to study. This is left for further research.

References

[1] D'Autume, A., K. Schubert and C. Withagen (2016): Should the Carbon Price Be the Same in All Countries? Journal of Public Economic Theory 18(5): 709-725.

[2] BASIC (2011): Equitable access to sustainable development: contribution to the body of scientific knowledge. *Technical report*, BASIC expert group, Bejing, Brasilia, Cape Town and Mumbai.

[3] Bode, S. (2004): Equal emissions per capita over time–a proposal to combine responsibility and equity of rights for post-2012 GHG emission entitlement allocation, European Environment 14(5): 300–316.

[4] Böhringer, C., B. Dijkstra and K. E. Rosendahl (2014): Sectoral and regional expansion of emissions trading, Resource and Energy Economics 37: 201-225.

[5] Bretschger, L. (2017): Equity and the Convergence of Nationally Determined Climate Policies, Environmental Economics and Policy Studies, 19(1): 1–14.

[6] Bretschger, L. (2013): Climate Policy and Equity Principles: Fair Burden Sharing in a Dynamic World, *Environment and Development Economics*, 18: 517–536.

[7] Bretschger, L. and S. Valente (2011): Climate change and uneven development, Scandinavian Journal of Economics 113(4): 825–845.

[8] Chichilnisky, G. and G. Heal (1994): Who should abate carbon emissions? An international viewpoint, Economics Letters (44): 443-449.

[9] Cramton, P., A. Ockenfels, and S. Stoft (2015): An international carbon-price commitment promotes cooperation. Economics of Energy and Environmental Policy 4 (2), 51-64.

[10] Dietz, S. and F. Venmans (2017): Cumulative carbon emissions and economic policy: in search of general principles, LSE Working Paper 283, London.

[11] Grasso, M. (2007): A normative ethical framework in climate change, Climatic Change 81(3): 223–246.

[12] Hoel, M. (1996): Should a carbon tax be differentiated across sectors? Journal of Public Economics 59 (1): 17-32.

[13] Hotelling, H. (1931): The Economics of Exhaustible Resources. Journal of Political Econonmy, 39: 137–175.

[14] Johansson-Stenman, O. and J. Konow (2010): Fair air: distributive justice and environmental economics, Environmental and Resource Economics 46: 147–166.

[15] Konow, J. (2003): Which is the fairest one of all? A positive analysis of justice theories, Journal of Economic Literature 41(4): 1188–1239.

[16] Lange, A., C. Vogt, and A. Ziegler (2007): On the importance of equity in international climate policy: an empirical analysis, Energy Economics 29: 545–562.

[17] Mattoo, A. and A. Subramanian (2010): Equity in climate change, Policy Research, Working Paper No. 5383, World Bank,Washington, DC.

[18] McKenzie, I.A. and M. Ohndorf (2012): Cap-and-trade, taxes, and distributional conflict, Journal of Environmental Economics and Management 63: 51-65

[19] Page, E.A. (2008): Distributing the burdens of climate change, Environmental Politics 17(4): 556–575.

[20] Posner, E.A. and D.A. Weisbach (2012): International Paretianism: a defense', University of Chicago Institute for Law & Economics Olin Research Paper No. 606, University of Chicago, Chicago, IL.

[21] Rebelo S. (1991): Long-Run Policy Analysis and Long-Run Growth, Journal of Political Economy, 99 (3): 500-521.

[22] Rose, A., B. Stevens, J. Edmonds, and M. Wise (1998): International equity and differentiation in global warming policy, Environmental and Resource Economics 12: 25–51.

[23] Stiglitz, J. E. (2015): Overcoming the copenhagen failure with flexible commitments. Economics of Energy and Environmental Policy 4 (2), 29- 36.

[24] Weitzman, M. (2014): Can negotiating a uniform carbon price help to internalize the global warming externality? Journal of the Association of Environmental and Resource Economists 1 (1/2): 29-49.

7 Appendix

7.1 Appendix A

From (4) and (5) we have for all $t = 0, 1, ...,$

$$p_t = \frac{1}{A} p_{t-1} + \gamma^t \frac{\nu q}{A}$$

and hence

$$\frac{\beta^t}{c_t} = \frac{1}{A} \frac{\beta^{t-1}}{c_{t-1}} + \gamma^t \frac{\nu q}{A}$$

or

$$\frac{1}{c_t} = \frac{1}{\beta A} \frac{1}{c_{t-1}} + \frac{\gamma^t}{\beta^t} \frac{\nu q}{A}$$

$$\frac{1}{c_t} = \frac{1}{\beta^t A^t}\left[\frac{1}{c_0} + \sum_{j=1}^{t}\left(\frac{\frac{\gamma^j}{\beta^j}\frac{\nu q}{A}}{\frac{1}{\beta^j A^j}}\right)\right]$$
$$= \frac{1}{\beta^t A^t}\left[\frac{1}{c_0} + \frac{\nu q}{A}\sum_{j=1}^{t}\gamma^j A^j\right]$$
$$= \frac{1}{\beta^t A^t}\left[\frac{1}{c_0} + \nu\gamma q\frac{1-\gamma^t A^t}{1-\gamma A}\right] \tag{A.1}$$

which immediately gives (6) in the main text.

Let us now prove (8). Indeed, we have

$$\frac{k_{t+1}}{c_t} = \frac{Ak_t}{c_t} - 1 = A\frac{c_{t-1}}{c_t}\frac{Ak_t}{c_{t-1}} - 1,\ t = 1, 2, \ldots.$$

We know that

$$\frac{c_{t-1}}{c_t} \xrightarrow[t\to\infty]{} \frac{\gamma}{\beta}$$

Since $\gamma A/\beta > 1$, there are three possible scenarios:

1. at some time k_{t+1}/c_t becomes negative;
2. k_{t+1}/c_t converges to $\frac{\beta}{\gamma A-\beta}$;
3. k_{t+1}/c_t goes to infinity.

The first scenario is impossible. The third one is also impossible because if k_{t+1}/c_t goes to infinity, then k_{t+1}/k_t converges to A and hence $\sum_{t=1}^{\infty}\gamma^t\nu k_t$ becomes infinitely large, which is impossible. Thus, only the second scenario is possible. This proves (8).

7.2 Appendix B. Proof of Proposition 2

Claim 1. *For E_0 such that $q > 0$, if E_0 increase, then π_t decrease for all $t = 0, 1, 2, \ldots$.*

Proof. Suppose that E_0 increases, but π_0 does not decrease. Taking into account (19), this implies that π_t do not decrease for all $t = 0, 1, 2, \ldots$. By (14), c_0/Ak_0 grows and hence $k_1 = Ak_0 - c_0$ is reduced. It follows that E_1 and $\pi_1 E_1$ increase and c_1/Ak_1 also increases while $k_2 = Ak_1 - c_1$ decreases. Repeating the argument we obtain that k_t shrinks for all $t = 1, 2, \ldots$. It follows that $\sum_{t=1}^{\infty}\gamma^t\nu k_t$ becomes strictly less than E_0, which implies that π_0 becomes zero, which is impossible. □

Claim 2. *For E_0 such that $q > 0$, if E_0 increase, then $1 + r_{t+1}$ also increase for all $t = 0, 1, 2, \ldots$.*

Proof. It is sufficient to note that by the first claim and (20), $1 + r_{t+1}$ is decreasing in π_t. $\square$

Claim 3. *For E_0 such that $q > 0$, if E_0 increase, then $\pi_t E_t$ decrease for all $t = 0, 1, 2, \dots$.*

Proof. Suppose that E_0 grows, but $\pi_0 E_0$ does not decrease. Then c_0 does not decrease. Therefore, by (14), k_1 and hence Ak_1 do not increase. Therefore, k_1 and hence Ak_1 do not increase. At the same time, (14) implies that s_0 does not decrease. Note also that $1 + r_1$ does not decrease by Claim 2. It follows that $Ak_1 + \pi_1 E_1 = (1 + r_1)s_0$ does not decrease. Thus, $\pi_1 E_1$ does not decrease.

Repeating the argument we obtain that k_t do not increase for all $t = 0, 1, 2, \dots$. It follows that $\sum_{t=1}^{\infty} \gamma^t \nu k_t$ does not increase and hence becomes strictly less than E_0, which implies that π_0 becomes zero, which is impossible. $\square$

This completes the proof of the proposition.

7.3 Appendix C. Proof of Proposition 3

First-order conditions for problem (22)-(24) are:

$$\tilde{p}_t^i = \lambda^i \frac{\beta^t}{c_t^i},\ i = 1, \dots, n,\ t = 0, 1, \dots,$$

$$A\tilde{p}_{t+1}^i = \tilde{p}_t^i + \gamma^{t+1} \nu^i \tilde{q},\ i = 1, \dots, n,\ t = 0, 1, \dots.$$

It follows that for all $i = 1, \dots, n$ and $t = 0, 1, \dots,$

$$\tilde{p}_{t+1}^i = \frac{1}{A}\tilde{p}_t^i + \gamma^{t+1} \frac{\nu^i \tilde{q}}{A},$$

and hence, in optimum,

$$\frac{\lambda^i}{\nu^i} \frac{1}{c_{t+1}^i} = \frac{1}{\beta A} \frac{\lambda^i}{\nu^i} \frac{1}{c_t^i} + \frac{\gamma^{t+1}}{\beta^{t+1}} \frac{\tilde{q}}{A} \tag{A.2}$$

and, therefore,

$$\frac{\lambda^i}{\nu^i} \frac{1}{c_t^i} = \frac{1}{\beta^t A^t} \left[\frac{\lambda^i}{\nu^i} \frac{1}{c_0^i} + \sum_{j=1}^{t} \left(\frac{\frac{\gamma^j}{\beta^j} \frac{\tilde{q}}{A}}{\frac{1}{\beta^j A^j}} \right) \right]$$

$$= \frac{1}{\beta^t A^t} \left[\frac{\lambda^i}{\nu^i} \frac{1}{c_0^i} + \frac{\tilde{q}}{A} \sum_{j=1}^{t} \gamma^j A^j \right]$$

$$= \frac{1}{\beta^t A^t} \left[\frac{\lambda^i}{\nu^i} \frac{1}{c_0^i} + \tilde{q}\gamma \frac{1 - \gamma^t A^t}{1 - \gamma A} \right],$$

which implies that

$$\lim_{t \to \infty} \frac{c_t^i}{c_t^j} = \frac{\lambda^i / \nu^i}{\lambda^j / \nu^j},\ i, j = 1, \dots, n.$$

and that

$$\lim_{t\to\infty}\frac{c^i_{t+1}}{c^i_t}=\frac{\gamma}{\beta},\ i=1,...,n.$$

By the same argument as in Appendix A,

$$\lim_{t\to\infty}\frac{k^i_{t+1}}{k^i_t}=\frac{\gamma}{\beta},\ i=1,...,n.$$

Thus, we have proved (25) and (26).

It follows from (A.2) that

$$\frac{\nu^i}{\lambda^i}c^i_t<\frac{\nu^j}{\lambda^j}c^j_t\ \Leftrightarrow\ \frac{\nu^i}{\lambda^i}c^i_{t+1}<\frac{\nu^j}{\lambda^j}c^j_{t+1},\ i,j=1,...,n,\ t=0,1,2,....$$

Since $\gamma A>1$, we have

$$\frac{\nu^i}{\lambda^i}c^i_t+\frac{1}{A}\frac{\nu^i}{\lambda^i}c^i_{t+1}+\frac{1}{A^2}\frac{\nu^i}{\lambda^i}c^i_{t+2}+...=\frac{\nu^i}{\lambda^i}Ak^i_t,\ i=1,...,n,\ t=0,1,2,.... \tag{A.3}$$

Therefore,

$$\frac{\nu^i}{\lambda^i}k^i_0<\frac{\nu^j}{\lambda^j}k^j_0\ \Leftrightarrow\ \frac{\nu^i}{\lambda^i}c^i_t<\frac{\nu^j}{\lambda^j}c^j_t,\ i,j=1,...,n,\ t=0,1,,.... \tag{A.4}$$

Moreover, from (A.2) we have

$$\frac{\nu^i}{\lambda^i}c^i_t<\frac{\nu^j}{\lambda^j}c^j_t\ \Rightarrow\ \frac{c^i_{t+1}}{c^i_t}>\frac{c^j_{t+1}}{c^j_t},\ i,j=1,...,n,\ t=0,1,....$$

Also we can rewrite (A.3) as

$$1+\frac{1}{A}\frac{c^i_{t+1}}{c^i_t}+\frac{1}{A^2}\frac{c^i_{t+2}}{c^i_t}+...=\frac{Ak^i_t}{c^i_t},\ t=0,1,...,$$

Therefore

$$\begin{aligned}\frac{\nu^i}{\lambda^i}c^i_t<\frac{\nu^j}{\lambda^j}c^j_t\ \Rightarrow\ 1+\frac{Ak^i_t}{c^i_t}&=1+\frac{1}{A}\frac{c^i_{t+1}}{c^i_t}+\frac{1}{A^2}\frac{c^i_{t+2}}{c^i_t}+...\\&>1+\frac{1}{A}\frac{c^j_{t+1}}{c^j_t}+\frac{1}{A^2}\frac{c^j_{t+2}}{c^j_t}+...=1+\frac{Ak^j_t}{c^j_t},\ i,j=1,...,n,\ t=0,1,....\end{aligned}$$

Since

$$k^i_{t+1}=Ak^i_t-c^i_t,\ i=1,...,n,\ t=0,1,...,$$

we obtain

$$\frac{\nu^i}{\lambda^i}c^i_t<\frac{\nu^j}{\lambda^j}c^j_t\ \Rightarrow\ \frac{k^i_{t+1}}{Ak^i_t}>\frac{k^j_{t+1}}{Ak^j_t},\ i,j=1,...,n,\ t=0,1,....$$

Taking into account (A.4), we get (27) in the main text.

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