Tax competition with asymmetric endowments in fossil resources[⋆,⋆⋆]

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Abstract

This paper contributes to the theoretical understanding of strategic interactions of governments on global markets for fossil resources and for capital. We analyze carbon taxes and subsidies and their impact on national welfare in a two country model with markets for capital and fossil resources, and asymmetric resource endowments. Resource poor countries have an incentive to tax the use of fossil fuels to appropriate the resource rent. Resource rich countries subsidize fossil fuel use to attract production factors in order to increase national income. We have two main results. First, we demonstrate that capital mobility has a taming effect on the incentives to tax and to subsidize resources. When taxing resources not only affects the international resource market, but also the international capital market, taxation is more distortionary and is thus more costly to governments. Second, while early studies of asymmetric tax competition found that small countries in terms of population are winners of tax competition, we show that with asymmetric resource endowments but a symmetric population size, there are no winners. Then, the Nash equilibrium of carbon tax competition is the least desirable outcome in terms of social welfare. A game structure similar to a Prisoner's Dilemma emerges and cooperation makes Pareto improvements over the Nash equilibrium possible.

Keywords: Tax competition, capital mobility, strategic instrument choice, carbon pricing, capital tax
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1. Introduction

The world order is changing. The vision of universal international cooperation as set out, for example, in the Charter of the United Nations and as many of us had believed in, is now fading again. Absent global cooperation or some form of world government, there is an urgent need for national policies that address global problems such as climate change, stymied growth due to the resource curse, and sustainable development on the national level. Accordingly, the architecture of the Paris Climate Agreement and the Agenda 2030 for Sustainable Development, as well as the conclusions of the 2015 conference in Addis Ababa on finance for sustainable development emphasize the role of national policies (Edenhofer et al., 2015; Franks et al., 2018). The process of being thrown back to national policies is intensified and accelerated by the Russian invasion of Ukraine, which lead to immediate and severe repercussions on global resource markets and calls for national policies to ensure energy independence.

National policies, however, do not leave foreign states unaffected. Low capital taxes may, for example, attract highly mobile capital from abroad triggering foreign policy responses. Asymmetric factor endowments may give rise to beneficial terms-of-trade effects, but also to strategic rent appropriation via carbon taxation. Knowledge about these strategic interactions of governments and their incentives to respond to foreign policies is therefore crucial for sound policy design.

This paper contributes to the theoretical understanding of strategic interactions of governments on global resource- and capital markets. We analyze different tax policies and their impact on national welfare in a model with international markets for capital and fossil resources.

Capital mobility has been shown to lead to tax competition[1] and a fiscal externality, that is, inefficient underprovision of local public goods (Wilson, 1986; Zodrow and Mieszkowski, 1986) but also to induce beneficial terms-of-trade effects if country asymmetries are taken into account (Bucovetsky, 1991; Schwerhoff and Edenhofer, 2013).

Recently, these standard models of capital mobility and capital tax competition has been extended to include fossil resources as a second mobile factor of production (Franks et al., 2017; Habla, 2018; Ogawa et al., 2016; Zimmermann, 2019). Moreover, country asymmetries haven been analyzed in papers that mainly provide quantitative numerical results (Parry, 2003; Brøchner et al., 2007) or analyze the implication for the slopes of tax reaction function (Vrijburg and de Mooij, 2016). But even though countries world-wide differ quite strongly in their endowments with fossil resources, only little is known about the implications of such asymmetries for the strategic behavior of governments when capital markets are taken into account. It is well known that resource-importing countries can implement carbon taxes strategically to appropriate a certain fraction of the exporters' resource rent (Karp, 1984; Amundsen and Schöb, 1999; Liski and Tahvonen, 2004). However, in this strand of literature, capital markets have not been taken into account. Maniloff and Manning (2018) do consider mobile capital in a partial equilibrium setting with asymmetric resource endowments, but neglect strategic behavior of resource importing regions and consider only capital in the resource extraction sector and not the whole economy.

We address this gap by systematically assessing the strategic use of domestic carbon taxes on international capital and resource markets, and the impact of asymmetries in

[1] See Keen and Konrad (2013) for an overview of the large literature on tax competition.

resource and capital endowments. We compare the impact of carbon taxes with other policy instruments, that is, capital taxes and trade policies that affect only imports and exports of factors. We thus implement a dynamic general equilibrium model of two countries similar to Franks et al. (2017) and test its robustness by extensive parameter variations, analyzing different model extensions, checking alternative policy instrument portfolios and varying the degree of asymmetry in resource endowments. It is based on early static models of tax competition by Wildasin (1988) and Hoyt (1991), who were the first to analyze large countries, which are able to affect the international rate of return on capital. We include a Ramsey growth model and combine it with the Hotelling model of resource extraction. This allows us to capture an essential difference between the two geographically mobile factors in our model, which is due to their different dynamic behavior. While capital requires investment, fossil resources do not, but instead give rise to a scarcity rent. To isolate the strategic incentives of governments concerned with the medium-run, we abstract from environmental externalities.

The model allows us to analyze the strategic incentives of governments in open economies to implement carbon taxes and subsidies. Resource rich and resource poor countries have different incentives. Absent any taxation, international factor mobility allows resources to flow along the gradient in productivity to the resource poor country and for capital to flow to the resource rich country. Given the possibility to tax, there are two channels by which both countries engage in strategic interactions. The first is the price-channel, the second the factor-channel. Using the price-channel, the resource poor country may try to appropriate the resource rent by taxing domestic resource use. The government of the resource rich country may try to counter this attempt by subsidizing domestic use of resources. When governments thus aim at manipulating prices on international markets, they do not take into account other countries' well-being and a pecuniary externality arises (DePeter and Myers, 1994). Using the factor channel, the resource rich country tries to attract more resources and – due to complementarity in production – more capital. An inflow of both factors, compared to the no-tax-case, increases national income, in particular also labor income (assuming that the marginal product of labor increases with increasing capital or resource use).[2] The latter channel can be exploited by the resource rich country, but for the resource poor country it induces a trade-off. By increasing the carbon tax the resource poor country can appropriate more of the resource rent, but at the same time it causes an outflow of mobile factors abroad and hence a reduction of national income, in particular labor income.

In this paper, we make two contributions to the analysis of tax competition on capital and fossil resource markets with asymmetric resource endowments. Our first contribution is to show the implications for carbon taxes of including international capital markets and capital taxes explicitly in the analysis. If capital cannot move freely on an international market, the factor channel becomes less important. Then, a resource poor country can tax carbon more heavily and thus appropriate more of the resource rent. It does not have to fear the outflow of capital. The resource rich country can only attract one type of production factor and thus subsidizes domestic resource use more than under capital mobility. Comparing the cases of mobile and of fixed capital shows that international integration of capital markets can have a substantial impact on the strategic use of carbon taxes. Going from nationally segmented capital markets to international

[2] Such rent-seeking behavior has been described by Bucovetsky (1995).

capital mobility changes average tax and subsidy rates by a factor of 1.1 to 2. Moreover, it turns out that this result is robust with respect to the availability of capital taxes.

Our theoretical finding that capital mobility has a taming effect on carbon taxation in resource importing countries can rationalize a stylized fact related to the pollution haven hypothesis: An increase in trade-openness leads to a reduction of the stringency of domestic environmental regulation (Kim and Lin, 2022). These authors write that "[when] facing intensive foreign competition due to greater trade openness, governments of countries with more stringent pollution control may be inclined to loosen it so as to protect domestic industries and employment."[3]

Our second contribution is to identify and analyze the pay-off structure of the game that emerges from the strategic interaction of the two countries' governments. Our results complement the seminal findings of Bucovetsky (1991) and Wilson (1991). In their models, the population-wise small country is better off under capital tax competition than under a cooperative solution with the constraint that there is a uniform tax in both regions. In that case, small countries will oppose cooperation. This suggests that *a priori* cases can emerge in which one player's pay-off in the Nash equilibrium is so beneficial, that this player could only lose in a cooperative equilibrium with certain constraints.

The question arises if this is not only the case for capital markets, but also for international resource trade. We focus on fossil resources and the constraint for cooperation that no cash transfers are possible (but tax rates may still differ). Doing so changes the pay-off structure of the game. We show that a "small" country – in the sense that it is relatively resource poor instead of having a small population – is worse off under carbon tax competition than under cooperation. Within this game structure, we find that Pareto improvements are possible.

Our results are robust under a wide range of alternative assumptions about the degree of asymmetry in resource endowments, other parameter values, the introduction of different model extensions and the availability of additional tax instruments.

The remainder of the paper is structured as follows. After a brief discussion of related literature in Section 2, we describe the model and its calibration in Sections 3 and 4 . In Section 5 we describe our results. In Section 6 we discuss the robustness of our results with respect to alternative assumptions about the model structure. In Section 7, we extend our basic model to include publicly financed infrastructure and trade-specific policy instruments (import tariffs and export duties on capital and resource markets). Here, we also briefly discuss the implications of setting a global minimum capital tax. We conclude with Section 8.

2. Related literature

The literature on capital mobility and tax competition is vast. The strand that is most relevant to the present paper deals with the role of asymmetries between regions and countries. Here, we briefly summarize the most relevant results that this strand has produced.

[3]However, they also discuss an opposing effect related to the Porter hypothesis. Trade openness may make innovation toward clean and energy-efficient technology desirable since it reduces costs. Hence, trade openness may also stimulate stricter environmental policy. Since our model abstracts from differences in (production) technology as well as endogenous technological change, we have effectively muted this latter channel.

In their seminal contributions, Bucovetsky (1991) and Wilson (1991) show that asymmetry in population of the jurisdictions complicates a coordination of tax policies that would resolve the inefficiency: smaller jurisdictions gain from tax competition and might hence veto tax harmonization. Bucovetsky (1995) extends the analysis of strategic interactions by allowing for two mobile factors (labor and capital) and one immobile factor (land). Then, Pareto-improvements over the Nash equilibrium are theoretically possible. However, if a top level government implements policies aiming at such Pareto-improvements, the lower level jurisdictions have the power to neutralize them.

Peralta and van Ypersele (2005) find that capital mobility brings efficiency improvements in an economy with asymmetric capital and population endowments because capital is used where it is most productive. Tax competition, where capital importers tax and capital exporters subsidize capital, reduces the gains from liberalization of capital markets as the different tax levels work against the (efficient) equalization of productivities. Putting constraints on tax coordination as a way to make tax harmonization feasible is explored in Peralta and van Ypersele (2006). They show for asymmetry in endowments (labor and capital) that coordination on tax ranges is always accepted by all – unlike the alternative tax reform of minimum taxes explored in the same study. Hwang and Choe (1996) investigate (two) countries that differ in their endowments of labor and capital and use regional capital taxes to provide public services. In equilibrium, capital taxes are not uniform as would be efficient. Hwang and Choe (1996) show that a central government policy (excise subsidy and income transfers) that equalizes consumption and utility levels across countries restores efficiency. DePeter and Myers (1994) show that asymmetry induces a pecuniary externality, which they contrast form the fiscal externality first identified by Wilson (1986) and Zodrow and Mieszkowski (1986). The pecuniary externality arises from the fact that one jurisdiction's decisions on how to set taxes do not take into account the change of the interest rate, which influences well-being in other jurisdictions.

Regional asymmetries are generalized from endowment differences to the case of heterogeneous production function in Taugourdeau and Ziad (2011) who show existence and uniqueness of the Nash Equilibrium in the resulting tax competition game. Kempf and Rota-Graziosi (2010), too, adopt the assumption of asymmetric production technologies when they endogenize timing of decision in otherwise standard Wildasin-type tax competition. While they find that their results are sensitive to the degree of asymmetry, they point out that heterogeneous production functions are not essential to their result, as asymmetric endowments (and hence ex-post asymmetry in productivity) would yield the same conclusions.

Devereux et al. (2008) and Pieretti and Zanaj (2011) analyze tax competition with more than one instrument. The former introduce a model that allows governments to set statutory tax rates and effective marginal tax rates on capital. The latter allow governments to choose both the level of public spending and the capital tax rate.

In our model, we also analyze governments that can implement two policy instruments at the same time. However, the novelty in our model is to introduce fossil resources in addition to capital as a second factor of production. We compare the strategic properties of capital taxes with those of a carbon tax.

In general, the literature on tax competition with asymmetric countries reviewed above does not consider the presence of an international market for fossil resources. In turn, much of the literature on international resource markets abstracts from capital markets. We close this gap by analyzing strategic interactions of governments on global markets for fossil resources and for capital.

3. The model

We implement a differential game based on a Ramsey-type general equilibrium growth model. There are two countries, each populated by an identical set of representative economic agents: a household, a final goods producing firm, and a fossil resource extracting firm. We allow for asymmetric endowments with fossil resources in situ. As a convention, we will always assume that country 1 is the resource poor country and country 2 is the resource rich country, whenever endowments are asymmetric.

3.1. International markets

The countries are labeled by the index $j \in \{1, 2\}$. They are linked by the international markets for capital and fossil resources. We distinguish between the final goods producing firms' demand for capital $K^d_{j,t}$ and resources $R^d_{j,t}$ at time t, household's capital assets, that is, the capital supply $K^s_{j,t}$, and the extracting firm's supply of resources $R^s_{j,t}$ and demand for capital $K^R_{j,t}$, which they require to extract the resource. Households own only the domestic firms (final goods and extraction sector) but rent out their accumulated capital and sell the fossil resource to any firm, domestic or abroad. Renting capital to a firm abroad does not afford them any ownership claims abroad, and we assume that capital and resources move around until the prices for each factor are equal in all countries. Thus, the international capital market is described by

$$K^s_{1,t} + K^s_{2,t} = K^d_{1,t} + K^R_{1,t} + K^d_{2,t} + K^R_{2,t} \quad \forall t, \tag{1}$$

$$r_{1,t} = r_{2,t} = r_t \quad \forall t, \tag{2}$$

where r is the interest rate. For the resource market and the price of fossil resources p, we have

$$R^s_{1,t} + R^s_{2,t} = R^d_{1,t} + R^d_{2,t} \quad \forall t, \tag{3}$$

$$p_{1,t} = p_{2,t} = p_t \quad \forall t, \tag{4}$$

Labor is significantly less mobile than capital or fossil resources. Thus, we assume in our model that labor is fixed in supply and may not move across country borders. A further market for final goods is not included as we assume that there is only one final goods producing sector. Firms pay the households and resource owners with their output of the final good.

3.2. Agents of the national economy

A large number of households live in each of the two countries. Output is produced by a large number of competitive firms which use labor, private capital, and fossil resources as inputs to produce a homogeneous final consumption good. The two countries are endowed with differing stocks of fossil resource, thus the firms in the resource poor country have to import them. Fossil resources are extracted in both countries by a large number of resource owners who sell them on the international resource market to the firms in the two countries.

The governments of the two countries influence the economy by implementing Ramsey-optimal policies, i.e. the government maximize household utility subject to the equilibrium of the economy (cf. Schmitt-Grohé and Uribe 2010).[4] The following optimization problems characterize the individual economic agents' behavior.

To determine the first order conditions, we use a maximum principle for discrete time steps as given in Feichtinger and Hartl (1986). We use their concept of the *discrete Hamiltonian* which is more convenient than the equivalent formulation of the optimization problems with Lagrangians. In the following we shall use the term *Hamiltonian* in this sense.

The representative household.. The representative household in country j derives instantaneous utility from per capita consumption $\frac{C_{j,t}}{L_t}$. Aggregate consumption in country j at time t is $C_{j,t}$ and L_t is population and at the same time labor. The supply of labor is given exogenously and we assume it to be equal in the two importing countries. Utility is given by the constant intertemporal elasticity of substitution (CIES) utility function

$$U(C_{j,t}/L_t) = \frac{(C_{j,t}/L_t)^{1-\eta}}{1-\eta}, \tag{5}$$

where $1/\eta$ is the intertemporal elasticity of substitution.

To improve readability, we will omit the country index j in the description of the household, the firms in the final goods sector and the resource extraction sector, and the government whenever no ambiguity arises. The household maximizes its welfare W^{HH} subject to the budget constraint (7) and the equation of motion of the capital it supplies, K^s (8).

$$\max_{C_t/L_t} \quad W^{HH} = \sum_{t=0}^{T} U(C_t/L_t)\left(\frac{1}{1+\rho}\right)^t \tag{6}$$

$$\text{subject to} \quad C_t + I_t = r_t K_t^s + w_t L_t + \Pi_t^F + \Pi_t^R + \Gamma_t \tag{7}$$

$$\text{and} \quad K_{t+1}^s = K_t^s(1-\delta) + I_t. \tag{8}$$

The capital stock depreciates at the annual rate δ. The household in country j discounts future utility according to its pure rate of time preference ρ. It rents out the capital that it supplies, K^s, on the global capital market and earns income according to the world interest rate r. Further, the household receives labor income according the exogenously given time path of labor and the endogenously determined wage rate w. The profits of the final goods firm Π^F and the resource extracting firm Π^R accrue to the household. The government may use tax revenue for lump sum transfers $\Gamma \geq 0$ to the household.

[4]The Ramsey approach to optimal policies is common not only in monetary economics (Schmitt-Grohé and Uribe, 2010), see, for example, applications in the context of environmental economics (Annicchiarico and Di Dio, 2017) or financial frictions (Itskhoki and Moll, 2019). The structure of the interaction of government and other economic agents is that of a Stackelberg game, where the government acts in anticipation of all agents' reactions to the policy instruments, that is, the government act as a Stackelberg leader to an economic of Stackelberg followers.

The discrete Hamiltonian is given by

$$\mathcal{H}_t^{HH} = U(C_t/L_t) + \lambda_t \left[(1 + (r_t - \delta))\, K_t^s + w_t L_t + \Pi_t^F + \Gamma_t - C_t \right],$$

and thus the first order and terminal conditions for the control and costate variables C and λ are

$$\frac{L_t^{\eta-1}}{C_t^{\eta}} = \lambda_t, \tag{9}$$

$$\lambda_{t-1}(1+\rho) = \lambda_t\,(1 + r_t - \delta)\,, \tag{10}$$

$$(I_T - (1-\delta)K_T^s)\,\lambda_T = 0. \tag{11}$$

The final goods production sector.. The representative firm is assumed to be a price taker. Its output is given by a neoclassical production function, which depends on three input factors – capital, labor, and fossil resources, denoted by $Y = F(K^d, L, R^d)$. For our calculations we use a nested constant elasticity of substitution (CES) function. On the lower level, private capital K^d, which the firm may demand on the global capital market, is combined with labor. On the upper level, fossil resources R enter in production. The production function takes the form

$$F(K_t^d, L_t, R_t^d) = \left[\alpha_1 (A_{R,t} R_t^d)^{s_1} + (1-\alpha_1)\mathbf{X}(K_t^d, L_t)^{s_1} \right]^{\frac{1}{s_1}}, \tag{12}$$

$$\text{where} \qquad \mathbf{X}(K_t^d, L_t) = \left[\alpha_2 (K_t^d)^{s_2} + (1-\alpha_2)(A_{L,t} L_t)^{s_2} \right]^{\frac{1}{s_2}}.$$

The exponents s_i, $i = 1, 2$, are determined by the respective elasticities of substitution σ_i via $s_i = \frac{\sigma_i - 1}{\sigma_i}$. We assume $\sigma_1 < 1$,[5] and for the share parameters it holds that $\alpha_i \in (0, 1)$, $i = 1, 2, 3$. $A_{\zeta,t}$ is the productivity of the factor $\zeta = R, L$ and is in both cases assumed to increase over time due to exogenous technological change. The parameters are chosen in accordance with empirically observed output and consumption growth rates:

$$\gamma_{\zeta,t} = \gamma_{\zeta,0} e^{-d_\zeta t}$$

$$A_{\zeta,t+1} = A_{\zeta,t} \left(1 + (\frac{\gamma_{\zeta,t}}{1 - \gamma_{\zeta,t}}) \right), \quad A_{\zeta,0} \text{ given,}$$

where $\zeta = L, R$.

The production technology (12) exhibits constant returns to scale in all inputs. The firm produces output with the technology given by (12), rents capital at the market interest rate r_t, pays workers their wage w_t, and pays the price p_t for the fossil resources it uses in each period. In addition, we assume that it may have to pay corporate taxes, which we approximate by an ad valorem tax on capital τ_K, or a source based carbon tax τ_R, to the government. The firm's objective is to choose the amount of capital, labor, and fossil resources it demands in each period which maximizes profit for all points t in

[5] See Franks et al. (2017) for more details on the calibration and choice of model parameters.

time,

$$\max_{K^d,L,R^d} \pi^F = F\left(K^d, G, L, R^d\right) - r\left(1+\tau_K\right)K^d - wL - (p+\tau_R)R^d.$$

Differentiation with respect to K, L, and R yield the three first order conditions, which equate the marginal product of the private input factors with their respective after-tax prices:

$$F_K = r(1+\tau_K) \tag{13}$$
$$F_L = w \tag{14}$$
$$F_R = p + \tau_R \tag{15}$$

The fossil resource sector.. Each country j is endowed with an exhaustible stock of a fossil resources of S_j gigatons of carbon, owned by a representative extraction firm. The firm extracts the stock at the annual rate of R^s_t using capital K^R. Thus, we have

$$S_{t+1} = S_t - R^s_t \tag{16}$$
$$\text{and} \quad R^s_t = \kappa(S_t)K^R_t \tag{17}$$

where $\kappa(S_t)$ decreases as more of the resource is extracted (we use the same calibration as in Kalkuhl et al., 2012). The calibration of extraction costs is based on Rogner (1997). We assume that resources with the lowest extraction costs are extracted first. The productivity κ is hence assumed to decline with increasing cumulative extraction.

$$\kappa_t = \frac{\chi_1}{\chi_1 + \chi_2\left(\frac{S_0 - S_t}{S_0}\right)^{\chi_3}} \tag{18}$$

The firm sells the resource on the international market to maximize the net present value (NPV) of profits,

$$\max_{R^s_t} \sum_t \pi^R_t \,\Pi^t_{s=0}(1 + r_s - \delta)^{-1}, \tag{19}$$
$$\text{where} \quad \pi^R_t = p_t R^s_t - K^R_t r_t \tag{20}$$

taking into account the resource constraint (17), the equation of motion for the stock (16). The discrete Hamiltonian then reads

$$\mathcal{H}^R_t = \left(p_t - \frac{r_t}{\kappa_t(S_t)}\right)R_t + \lambda^R_t(S_t - R^s_t),$$

and thus the first order and terminal conditions for the control and costate variables R and λ^R are

$$\lambda^R_t = p_t - \frac{r_t}{\kappa_t}, \tag{21}$$
$$\lambda^R_t - \lambda^R_{t-1}(1 + r_t - \delta) = -\frac{r_t R_t \chi_2 \chi_3}{\chi_1 S_0}\left(\frac{S_0 - S_t}{S_0}\right)^{\chi_3 - 1}, \tag{22}$$
$$\lambda^R_{T-1} S_T = 0. \tag{23}$$

The government.. The firms, the resource owners, and the households take all taxes, the interest rate and the price for fossil resources as given. The government sets the Ramsey-optimal policies, i.e. government policies maximize household utility subject to the market equilibrium of the decentralized economy. This way, the government can influence international factor prices and the international and intertemporal allocation of production factors. However, one country's government does not take into account how its choices about tax paths affect the other country's welfare (since policy choices affect international factor markets). Therefore, a pecuniary externality arises (DePeter and Myers, 1994).

The government of country j anticipates the general equilibrium response of the economy. It takes into account all first order conditions, budget constraints, terminal conditions, etc. from the other agents' optimization problems when deciding on the tax paths. The government distributes the tax revenue to the domestic households as lump sum transfers. Country j's government's problem thus reads

$$\max_{\tau_K,\tau_R} \quad W_j = \sum_{t=0}^{T} L_t U\left(C_t/L_t\right)\left(\frac{1}{1+\rho}\right)^t$$
$$\text{subject to } \Gamma_t = r_t \tau_{K,t} K_t^d + \tau_{R,t} R_t^d$$

and Equations (1) - (4), (7), (8), (13) – (16), and (9) – (23).

3.3. Equilibria of the economy

The overall allocation of economic resources for production can be determined either under the assumption of a social planner, or a decentralized market economy. In the latter case, the governments in the two countries can either compete and use their policy instruments to maximize their domestic household's utility – or, the two governments can cooperate in choosing their policy instruments to maximize the sum of both households utility. In all cases, we frame the optimization problem as a non-linear program and solve the economy using the GAMS software (Brooke et al., 2005). The GAMS code is included in the digital supplementary material. In the following, we describe each equilibrium concept individually.

Social planner equilibrium.. The social planner solves the optimization problem

$$\max_{C_{j,t},I_{j,t}} \quad W^{SP} = \sum_{j=1,2}\sum_{t=0}^{T} L_{j,t} U\left(C_{j,t}/L_{j,t}\right)\left(\frac{1}{1+\rho}\right)^t \qquad (24)$$
$$\text{subject to } F(K_{j,t}^d, L_{j,t}, R_{j,t}^d) = C_{j,t} + I_{j,t},$$

clearing of the international capital and resource markets (1) and (3), the production technologies of final goods and fossil resources (12) and (17), and the equations of motion of the stocks of capital (8) and resources (16).

Nash equilibrium.. All economic agents except the governments take the strategies of the other agents as given. Following the Ramsey approach to optimal policies, governments decide policies in anticipation of the reactions of the firms in both sectors and households. Technically, in the Ramsey approach, the government is a Stackelberg leader to an economy with agents that act as Stackelberg followers (Dockner, 2000).

Inherent in Ramsey-optimal policies is the assumption that governments can commit to the policies they announce.[6]

Each country's government faces its local agents and anticipates their reaction. We further assume that the government also anticipates the reactions of each foreign household, firm, and the resource owner. This makes the government a Stackelberg leader of all firms and households, both domestic *and* foreign.

At the same time, one country's government also faces the other country's government, a Stackelberg leader of the global economy as well.[7] Thus, governments sit at two game tables – here a Stackelberg and there a simultaneous move game. In the former sub-game, the governments have to make decisions about how to influence the behavior of private actors through influencing prices (rental rate of capital, resource price). In the latter, all governments can interact strategically with each other through the choice of policy instruments.[8]

Each government takes the strategies of the other government as given when choosing its own strategy. In doing so, it anticipates the international movement of capital and fossil resources, but also the behavior of domestic and foreign households, firms, and resource owners in response to the policy instrument choice.

More formally, the objective of the government in country j is to maximize its payoff, that is, its welfare W_j. The strategies of the governments are $\{\tau^j_{\zeta,t}\}$ where $t \in \{1, ..., T\}$ and $\zeta \in \{K, R\}$. Each government takes as given the other government's strategies.

The cooperative solution.. The Stackelberg game structure described above remains the same, both in the non-cooperative and the cooperative solution. In contrast to non-cooperation, though, we obtain the cooperative solution by calculating those policies $\{\tau^j_{\zeta,t}\}$, where $j = 1, 2,\ \ t \in \{1, ..., T\}$, and $\zeta \in \{K, R\}$, that maximize the joint welfare of both countries,

$$\max_{\{\tau^j_{\zeta,t}\}_{j,\zeta,t}} W^{COOP} = W_1 + W_2. \tag{25}$$

$$\text{subject to } \Gamma_{j,t} = r_t \tau^j_{K,t} K^d_{j,t} + \tau^j_{R,t} R^d_{j,t}$$

and Equations (1) - (4), (7), (8), (13) – (16), and (9) – (23).

Social welfare.. To evaluate the outcomes of different policy scenarios, we compare each scenario with the social planner's solution. In particular, we follow Kalkuhl et al. (2012) and express the welfare loss of a policy scenario relative to the social optimum in balanced growth equivalents, so-called BGE welfare losses, as introduced by Anthoff and Tol (2009) (see Appendix Appendix A for the mathematical definition).

[6]Due to this decision structure, at least in theory time inconsistencies could arise. However, we have checked whether governments have an incentive to deviate from the initially announced tax paths and found no significant deviations (see Franks et al., 2017, for more details).

[7]Strictly speaking, the national governments are only Stackelberg leaders of the subgame in which they determine their own policy instruments optimally, taking the other governments' policy instruments as given and taking the reactions of all other economic agents into account. In the present study the term Stackelberg leader always refers to this specific meaning.

[8]See Appendix Appendix B

Description		symbol	value	range	sources
Intertemporal elasticity of substitution		η	1.1		
Pure rate of time preference		ρ	0.03		
Annual depreciation rate of capital		δ	0.025		
Share parameter of fossil resource		α_1	0.05		Edenhofer et al. (2005)
Elasticity of substitution between Z and R		σ_1	0.5	0.25 – 0.92	Hogan and Manne (1979) Kemfert and Welsch (2000) Burniaux et al. (1992) Markandya and Pedroso-Galinato (2007)
Share parameter of general capital **Z**		α_2	0.42		Caselli and Feyrer (2007)
Elasticity of substitution between K and L		σ_2	0.7		 Coenen et al. (2012) Otto and Voss (1998)
Initial labor productivity		$A_{L,0}$	6		
Initial growth rate of A_L		$\gamma_{L,0}$	0.026		
Decline rate of labor productivity		d_L	0.006		
Initial resource use productivity		$A_{R,0}$	1		authors' calibration
Initial growth rate of A_R		$\gamma_{R,0}$	0.005		"
Decline rate of resource use productivity		d_L	0.001		"
Initial world capital	[tril. US$]	K_0	165		
Initial world resource stock	[GtC]	S_0	4000		
Initial world population	[bill.]	L_0	6.5		
Population maximum	[bill.]	L_{max}	9.5		
First period [year]		t_0	2010		
Last period [year]	[years]	T	2085		
Time step	[years]	Δ	5		
Scaling parameter		χ_1	20		
Scaling parameter		χ_2	700		
Slope of Rogner's curve		χ_3	2		

Table 1: List of model parameters. If source not indicated otherwise, values are chosen in accordance with Kalkuhl et al. (2012) and Edenhofer et al. (2010).

4. Calibration and implementation of model

We calibrate the model to the global level. The model parameters are chosen such that initial output, capital stock and population match the observed global data for the year 2010. Table 1 summarizes the parameters used in the model. If not otherwise indicated, we have chosen their values in accordance with the closely related model PRIDE[9], as introduced in Kalkuhl et al. (2012), and the model comparison exercise referenced therein, Edenhofer et al. (2010). The parameters of the production function are calibrated according to the empirical literature. We insert the elasticities of substitution between the respective factors directly.

5. Results

We present our main results in the following. We begin by describing the incentives of resource poor and resource rich countries to use carbon taxes and subsidies strategically in Section 5.1. This provides the reader with a basic intuition on quantitative and qualitative model behavior, which helps to interpret our main results. In Section 5.2, we explain the impact of capital mobility on our results by comparing scenarios in which capital is mobile with scenarios without capital mobility. Then, in Section 5.3,

[9]Both our model and PRIDE are capable of calculating 2nd best solutions in a decentralized economy with several different economic actors. Both models are formulated as non-linear programs which are implemented with the GAMS software (Brooke et al., 2005).While PRIDE involves a more detailed energy sector and a broader set of policy instruments, it does not represent multiple countries, but only one global closed economy.

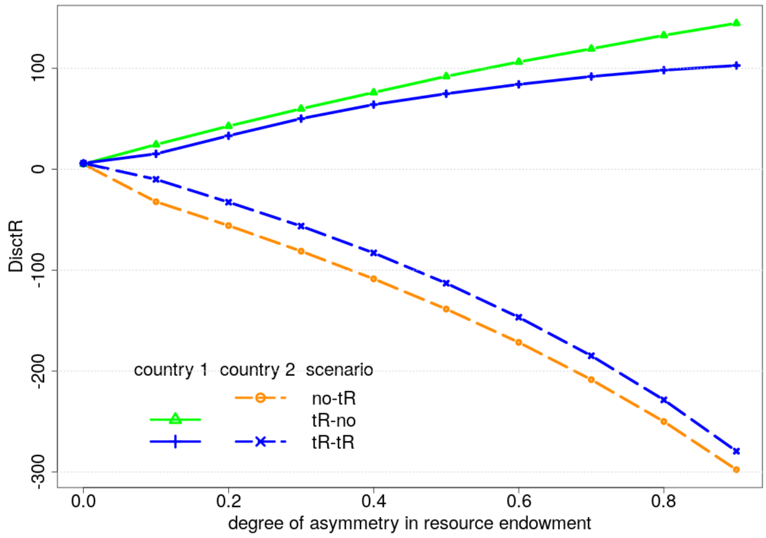

Figure 1: Net present value (NPV) of carbon tax revenues in each country [10^{12} US$] as function of the degree of asymmetry in resource endowments ϕ: Let total endowments be S_0, then we vary $\phi \in (0,1)$ to determine the endowments S_j, $j = 1,2$, according to $S_j = \frac{S_0}{2}[(1-\phi)+2(j-1)\phi]$. If both countries can use carbon taxes (the "tR-tR" scenario), the resource rich country subsidizes resources and the poor country taxes resources. If only the resource rich country may use the carbon tax ("no-tR"), it subsidizes even more. Similarly, if only the resource poor country may use the carbon tax, it raises even higher taxes.

we discuss the game structure in terms of payoffs to different strategies and we show the Pareto frontier for the social planner solution and for the decentralized market economy. The latter determines the scope for Pareto improvements over the Nash equilibrium in carbon taxes, which turns out to be the least desirable outcome in terms of social welfare.

5.1. Strategic incentives to use carbon taxes when capital and resources are mobile

Before discussing our two main results, this section describes how the strategic incentives of resource poor and resource rich countries' government differ. The resource poor country (by our convention country 1) has an incentive to raise a positive carbon tax on domestic production, and the resource rich country (country 2) has an incentive to subsidize domestic use of fossil resources. Both effects become more pronounced the higher the higher degree of asymmetry in resource endowment between the two countries is. We demonstrate this in Figure 1 using tax revenues; using tax rates instead would yield a similar picture.

5.1.1. Incentives of the resource poor country

The resource poor country can appropriate a part of the resource rent that otherwise accrues to the resource rich country by implementing a positive carbon tax. In particular, increasing the carbon tax rate not only reduces resource imports but lowers the global net-of-tax price of the fossil resource, and raises the consumer price for the domestic firms in the resource poor country. The carbon tax determines this wedge between gross and net price. The resource poor country appropriates resource rents to the extent that the net price is pushed below the initial net price level (we explain this in detail in the Appendix using Figure Appendix C.1). These counteracting effects on factor inflow

ξ	τ_R	π_R	Y^K	Y^L	C	I	welfare loss
0.5	79	17	992	1776	2416	447	0.01
0.75	113	16	985	1746	2417	443	0.004
1.0	145	16	978	1717	2416	440	-
1.5	201	15	968	1661	2410	435	0.01
2.0	248	14	960	1608	2399	431	0.04

Table 2: An exogenous variation of the carbon tax path around the optimum ($\xi = 1$) reveals the trade-off the government in the resource poor country faces. The table shows the net present value (NPV) in USD 10^{12} of the different components of the national budget of the resource poor country: carbon tax revenues τ_R, resource sector profits π_R, capital income Y^K, labor income Y^L on the income side, and consumption C and investments I on the expenditure side. The NPV of consumption doesn't peak exactly at $\xi = 1$ because the government does not maximize consumption itself, but rather the NPV of utility, which is a non-linear function of consumption. The last column shows BGE welfare losses (as defined in Section 3.3) relative to the optimal policy ($\xi = 1$) in percentage points.

and factor price are also known from models with a single mobile factor, e.g. Peralta and van Ypersele (2005), and creates an incentive for importer to tax imports.

Here, however, there is a second mobile factor to consider: for the resource poor country, an increase of its carbon tax also implies a shift of capital and resources away from domestic production towards production abroad (Figures Appendix C.2 and Appendix C.3). Hence, national income decreases, in particular also labor income. When the government of the resource poor country chooses the optimal carbon tax rate, it considers the trade-off between appropriating the rent and pushing mobile production factors out of the country. It does not take into account the resource rich country's well-being and, thus, a pecuniary externality arises (DePeter and Myers, 1994).

We illustrate the resource poor country's trade-off associated with small unilateral changes in the carbon tax in Table 2, assuming that the resource rich country owns 95% of all resource.[10] The table shows results for a scenario in which only the resource poor country may implement taxes and the resource rich country's government does not react. While increasing the tax also increases the resource rent appropriated (cf. revenues τ_R) , at the same time, it drives out production factors, reduces capital income (Y^K) and labor income (Y^L), and ultimately reduces consumption (C). As benchmark, we use the resource poor country's optimal carbon tax path $\{\tau_{R,t}\}_{t=0,...,T}$ which maximizes its welfare (last column). Subsequently, we calculate the equilibria for several variations of that optimal carbon tax path. More precisely, we vary the tax path exogenously by multiplying it with one time independent constant ξ, yielding $\{\xi\tau_{R,t}\}_{t=0,...,T}$, where we choose $\xi \in [0.5, 2]$. Moreover, the higher the carbon tax, the lower is the fraction of the appropriated rent in total tax revenues, as Figure 2 shows.
The main finding can be summarized as follows.

Proposition 1. *Resource poor countries have an incentive to tax the domestic use of fossil resources in order to appropriate the resource rent. However, this incentive is moderated by the adverse effect of a carbon tax to push mobile production factors out*

[10]The qualitative incentives to tax or to subsidize are independent of the degree of asymmetry in fossil resource endowments. As Figure 1 shows, as soon as fossil resource endowments are not symmetric, the resource rich country chooses a negative tax rate (a subsidy) and the resource poor country a positive tax rate.

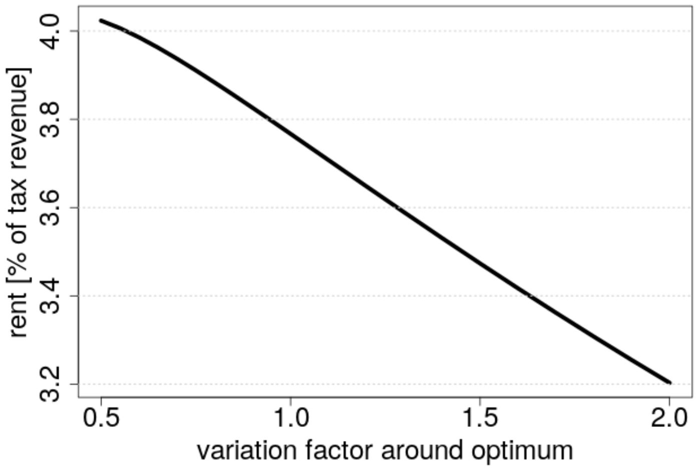

Figure 2: Appropriated rent as fraction of total carbon tax revenue in the resource poor country for a policy scenario in which only the resource poor country implements its optimal carbon tax. Here, we assume that the resource rich country owns 95% of all resource. On the x-axis, we vary the constant factor ξ by which we multiply the optimal carbon tax. For example, in case the resource poor country implements its optimal tax, we have $\xi = 1$ and the appropriated resource rent makes up about 3.7% of total carbon tax revenue.

of the country.

5.1.2. Incentives of the resource rich country

The resource rich country can attract production factors on the international factor markets by subsidizing the use of fossil resource in production (cf. Figure 1). The inflow of mobile production factors increase labor income due to complementarity. Moreover, it also makes extraction within the resource rich country more attractive. An increase in domestic extraction activity implies that more capital is needed in the resource sector. Accordingly, in the resource rich country, both capital demand by the final goods firm and by the resource extracting firm increase. However, the relative share of capital employed in the final goods sector decreases, and it increases in the extracting sector. In choosing the optimal subsidy, the government faces a trade-off. It takes into account that increasing the subsidy increases the use of factors in domestic production and hence increases labor income. On the other hand, the subsidies also raise the costs of resource extraction κ, which are a convex function of cumulative extraction – cf. Equations (17) and (18). The government also takes into account that the subsidy distorts the households' intertemporal savings decisions.

To illustrate the impact a subsidy in the resource rich country has, we exogenously vary the optimal path of the subsidy by a constant factor $\zeta \in [0.5, 2]$.[11] Table 3 and Figure 3 illustrate the consequences of deviating from the optimal path: Doubling the optimal subsidy rate implies an increase in the net present value of the profits the resource extracting firm makes (π_R). While also capital income (Y^K) and labor income (Y^L) increase, the increase in total income is not enough to offset the loss of consump-

[11] As benchmark case, we assume that only the resource rich country may implement its optimal subsidy path $\{\tau_{R,t}\}_{t=0,...,T}$. Subsequently, we vary the subsidy path exogenously by multiplying it with one time independent constant ζ, yielding $\{\zeta\tau_{R,t}\}_{t=0,...,T}$, where we choose $\zeta \in [0.5, 2]$.

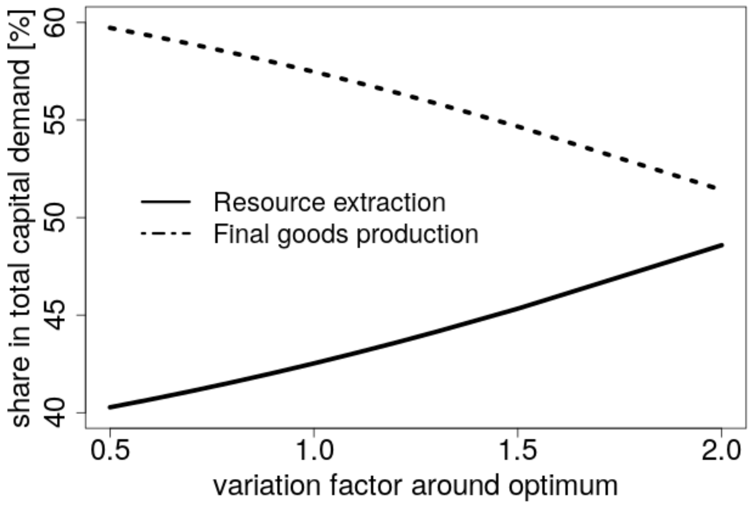

Figure 3: As the resource rich country increases its subsidy, relatively more capital is used for extracting the fossil resource and a smaller share is employed in the production of final goods.

tion (C) associated with the increase of the subsidy (cf. $-\tau_R$). The additional income is not used for consumption, but rather for increased investment (I) necessitated by the increased use of fossil resources. Accordingly, the share of total capital used for resource extraction increases and the share of capital used in the final goods sector decreases (Figure 3).

ζ	τ_R	π_R	Y^K	Y^L	C	I	welfare loss
0.5	-130	418	1182	1920	2815	575	0.02
0.75	-209	449	1211	1962	2821	594	0.01
1.0	-298	486	1247	2004	2823	616	-
1.5	-512	577	1336	2085	2813	673	0.03
2.0	-778	696	1453	2157	2781	747	0.13

Table 3: An exogenous variation of the optimal subsidy path indicates the trade-off the government in the resource rich country faces. NPV of carbon tax revenues τ_R, profits of the resource extracting firm π_R, capital income Y^K, labor income Y^L, consumption C and investments I [10^{12} USD]; and in the last column BGE welfare loss (as defined in Section 3.3) relative to the optimal policy ($\zeta = 1$) in percentage points.

We summarize the findings in the following proposition.

Proposition 2. *The resource rich country has an incentive to subsidize the use of fossil resources in order to increase labor income. This incentive is moderated by the adverse effect of the subsidy to raise extraction costs and to distort households' intertemporal saving decisions.*

5.2. How does capital mobility influence the strategic use of the carbon tax?

Rich and poor countries face trade-offs when imposing carbon taxes (τ_R) which are in part linked to the subsequent flows of capital as discussed above. To shed light on the

Scenario		$\tau_{R,1}$ (NPV)	$\tau_{R,2}$ (NPV)	$\tau_{R,1}$ (rate)	$\tau_{R,2}$ (rate)
τ_R - no	capital mobile	145	0	396	0
	capital immobile	157	0	542	0
no - τ_R	capital mobile	0	-294	0	-526
	capital immobile	0	-425	0	-827

Table 4: Net present value of carbon tax revenues [tril. US$] and average carbon tax rate [$/tC] for different policy scenarios under the assumption that the resource poor country (Country 1) owns 5% of all resources and the resource rich country (Country 2) owns 95%.

importance of capital mobility for equilibrium carbon taxes, we compare policy scenarios featuring capital mobility with policy scenarios featuring internationally immobile capital, ceteris paribus. In all scenarios considered in the present Section 5.2, we assume that the resource poor country owns 5% of all fossil resources and the resource rich country possesses 95%, as in the preceding section.[12]

Table 4 reports data for scenarios in which only one of the two countries' governments can implement its optimal carbon tax. We observe that capital mobility has a taming effect on the optimal unilateral policies. Without international capital trade, both governments choose higher taxes and subsidies, respectively.

If capital is mobile internationally, then a marginal increase in the carbon tax rate in the resource poor country induces a certain amount of resources to relocate abroad (recall Figure Appendix C.2), and, due to complementarity, also capital. This negative effect associated with carbon taxation limits the resource poor country's ability to appropriate resource rents. When capital cannot move internationally, the negative effect is less pronounced. Resources may relocate, but carbon taxes do not cause an outflow of capital, and thus the resource poor country's optimal carbon tax rate increases.

While capital mobility limits the resource poor country's ability to appropriate resource rents, its overall effect for that country's net present value of income is beneficial, as Figure 4 of the "τ_R - no" scenario illustrates. The figure shows the difference in income shares between the cases of immobile and mobile capital. The most notable impact of opening the borders to capital trade is the shift of capital income from the resource rich to the resource poor country. Opening the borders to capital trade allows the relatively abundant capital from the resource poor country to flow into the resource rich country, where it may earn a higher interest rate. Without capital mobility, interest rates in both countries differ, that is $r_{1,t} < r_{2,t}$, $\forall t$. Once we allow capital mobility, in the new equilibrium the international interest rate $\tilde{r}_t$ lies between the two national interest rates of the scenario without capital mobility, thus $r_{1,t} < \tilde{r}_t < r_{2,t}$, $\forall t$. The increase (decrease) in the interest rate for the households in the resource poor (rich) country coincides with an increase (decrease) in capital income and an increase (decrease) in investment. In the "no - τ_R" scenario, we observe the same qualitative impact on capital income, interest rates, and investments, as in the "τ_R - no" scenario (see Figure 5).
The main findings can be summarized as follows.

[12]The results in this section are robust under variations of the degree of asymmetry in resource endowments. That is, they hold as long as the resource rich country owns more than 75% of the global resource stock. See also Section 6.1 for a discussion.

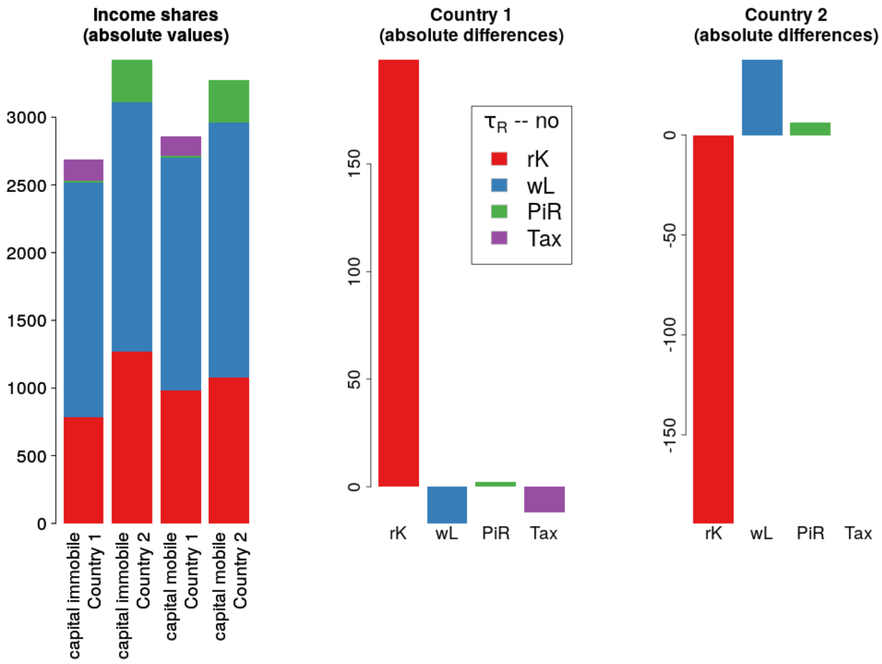

Figure 4: Comparing the NPV of national income for "τ_R - no" scenarios with and without capital mobility. Resources may be traded in both scenarios. The resource poor country (Country 1) implements its optimal carbon tax. National income is disaggregated into the shares of capital and labor, and the profits in the resource sector. The resource rich country (Country 2) owns 95% of all resources. If capital is mobile, the resource poor country implements lower taxes than if capital is fixed. With capital mobility, households in the resource poor country can invest their relatively abundant capital abroad where it is more scarce and hence more productive.

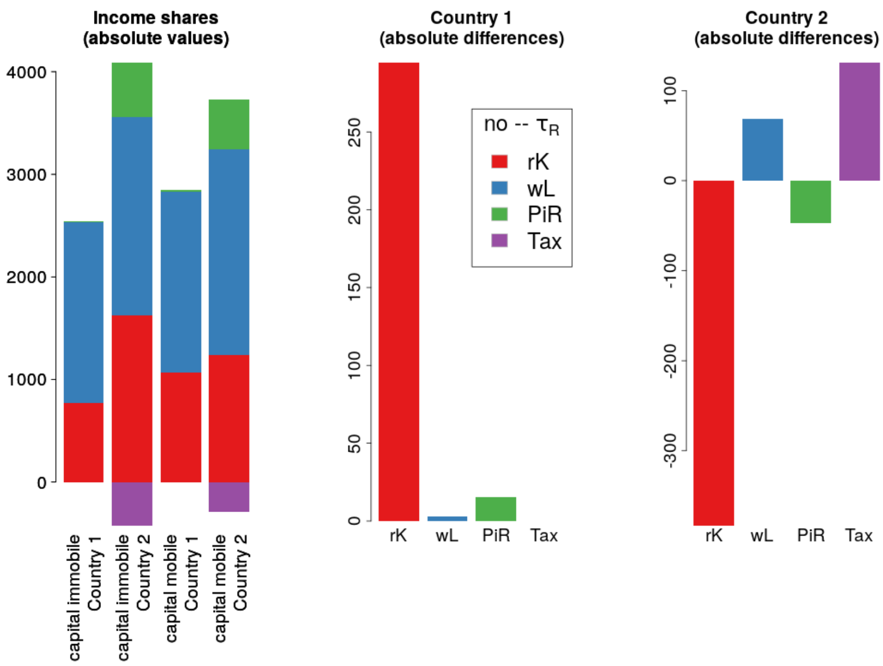

Figure 5: Comparison of "no - τ_R" scenarios with and without capital mobility, when the resource rich country (Country 2) implements its optimal subsidy on fossil resources and the resource poor country's government (Country 1) remains passive.

Proposition 3. *Comparing a scenario in which capital is mobile with a scenario in which it is not, we observe that for high degrees of asymmetry in fossil resource endowments, capital mobility has a taming effect on optimal unilateral carbon tax and subsidies. That is, both carbon tax/subsidy rates and public revenues/expenditures are lower when capital is mobile.*

5.3. Winners and losers of factor mobility and tax competition

Whereas tax competition in a symmetric setting often triggers a tragic race to the bottom, asymmetric tax competition has been shown to produce both winners and losers. In this section, we discuss who winners and losers of factor mobility and tax competition are, when both capital and fossil resources can be traded on international markets and either one or the other, or both countries implement carbon taxes or subsidies. We also consider the impact of the availability of capital taxes. In Section 5.3.1 we describe the model outcomes in terms of welfare for an economy with asymmetric resource endowments, assuming that 95% of all resources are owned by Country 2. Then, in Section 5.3.2, we discuss our observations.

5.3.1. Model data

We begin with an overview of the feasible allocations. In Figure 6, we show the allocations that a social planner can implement in the space of utility of the two countries.[13] The green curve delineates the Pareto frontier of the social planner economy. Given the utilitarian social welfare function (24) that simply adds up utility in both countries, the indifference curve is given by the straight gray line. The social optimum is marked in the figure. It is the point at which the indifference curve is tangent to the Pareto frontier.

If, instead of a social planner, the two governments would implement carbon taxes in both countries to maximize the sum of their social welfare (cf. Equation (25)), the Pareto frontier would be the one delineated by the blue curve. The social planner's solution and the cooperative solution differ.

Why does the cooperative solution differ from the solution of the social planner? To understand this, note that the social planner has much more freedom to allocate goods and factors than the two governments. For example, we do not allow for direct cash transfers in the cooperative equilibria. If additional instruments are available to the two governments, the outcomes under cooperation can be improved. If direct cash transfers are available, cooperating governments can move closer to the first best optimum, which the social planner implements. However, even if there are no direct cash transfers available, but both government implement optimal capital taxes in addition to carbon taxes, the Pareto frontier under cooperation moves closer to the Pareto frontier of the social planner. We illustrate this in the appendix in Figure Appendix C.4.

Finally, assume that all three instruments, capital- and carbon taxes as well as direct cash transfers, are available to the two cooperating governments. Even in that case they would not achieve the first-best optimum because there are convex extraction costs, which are different for the two countries. Cooperating governments have to take the behavior of the private extraction firms into account, which do not coordinate the timing of their extraction. Hence, resources are not always extracted where it is cheapest. A social planner would – in contrast – only see one big resource stock and could extract

[13]Note that on each of the two axes, we show the change in consumption in one country relative to the consumption level that each country would have in the social optimum.

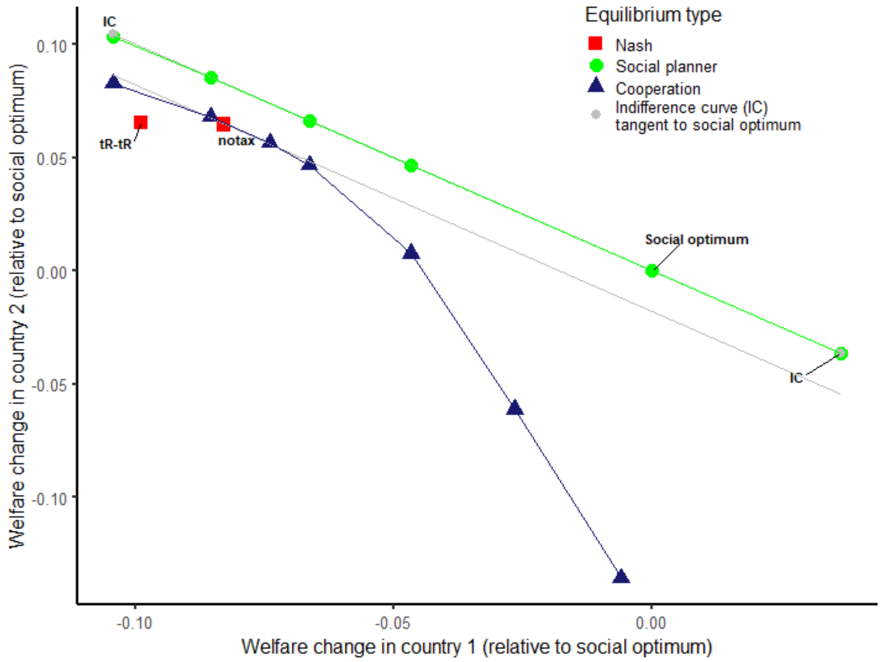

Figure 6: BGE Welfare change (as defined in Section 3.3) relative to the social optimum in Country 1 (resource poor) and Country 2 (resource rich) for different allocations a social planner can achieve, and for different allocations attainable by implementing carbon taxes in both countries cooperatively. The market outcome without any taxes is labelled as ”notax”, the Nash equilibrium with both countries setting their optimal carbon tax unilaterally is labelled as ”tR-tR”. The indifference curve that is associated with social welfare is tangent to the social optimum and labeled ”IC”. We also show the lower indifference curve tangent to the ”notax” scenario.

in such a way that extraction costs are always the lowest possible. Indeed, if extraction costs are zero, also cooperating governments can achieve the first best solution with only the carbon tax. Cooperating government are, thus, more constrained with respect to the timing of the resource extraction than the social planner. Hence, to achieve the first best solution in a world with positive extraction costs, cooperating governments would need an instrument that gives them perfect control over the resource extraction path. This could be achieved, e.g., by expropriation of the resource extracting firms. Indeed, if we assume in our model that the resource extracting sector is under control of the government, the social planner solution and the cooperative decentralized solution coincide (not shown). In the appendix, in Figure Appendix C.5, we show how decentral cooperative and centralized planner solution increasingly diverge in terms of the two countries' welfare levels when we increase extraction costs from zero up to our standard calibration.

In Figure 7 we show the outcomes for different policy scenarios, along with the indifference curve associated with social welfare tangent to the social optimum (connecting the grey dots labeled IC), and two indifference curves with lower welfare levels. The social optimum that a social planner implements is outside of the bounds of this figure. We observe that the policy scenarios involving non-cooperation induce a game situation for the two countries that is similar to a Prisoner's Dilemma. To see this, consider for simplicity only two possible strategies: to either implement a carbon tax/subsidy, or to leave the tax rate at zero. From the perspective of the social planner in our model, the most desirable combination of strategies for the two governments would be to leave tax rates at zero. As can be seen in Figure 7, this would result in a payoff vector lying on the

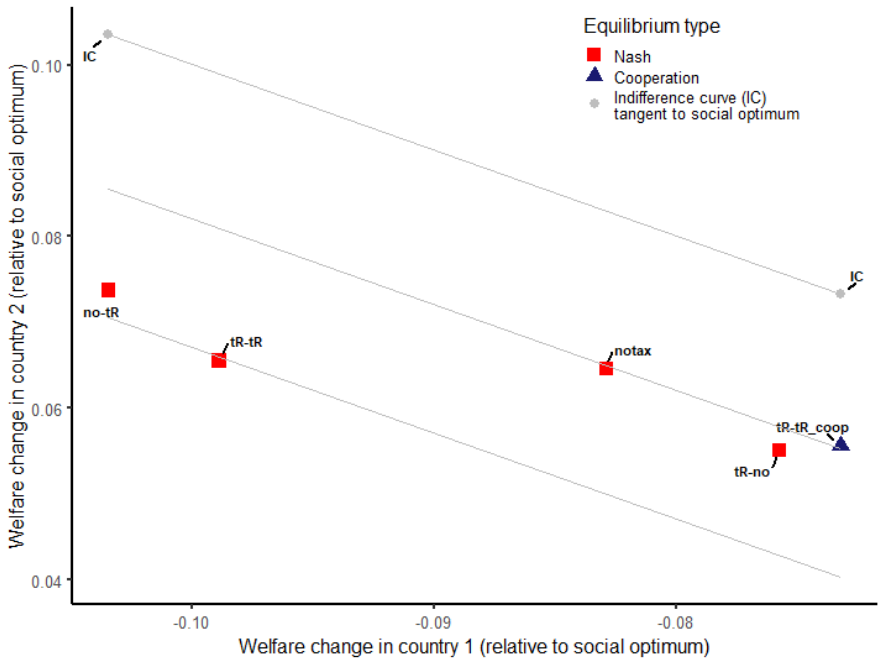

Figure 7: Welfare change (relative to social optimum) in country 1 (resource poor) and country 2 (resource rich) for different types of equilibria and different combinations of policy instruments. The indifference curve that is associated with social welfare is tangent to the social optimum and labeled "IC". We also show two lower indifference curves, one tangent to the "notax" scenario, and the other tangent to the "tR-tR" scenario.

highest possible indifference curve of the social planner. The Nash equilibrium in this game would be for both countries to implement their unilaterally optimal tax/subsidy. The Nash equilibrium is the least desirable outcome from the perspective of social welfare. The only difference to the Prisoner's Dilemma is that the resource rich country is about as well off in the Nash equilibrium as in the social optimum. In our standard calibration the resource rich country has a BGE welfare loss of a mere 0.006% when moving from the Nash equilibrium ("tR-tR") to the socially desirable outcome ("notax"). However, we find that under small variations of certain parameters, a true Prisoner's Dilemma emerges (see Section 6).

5.3.2. Discussion

When countries are symmetric, tax competition causes the well know race to the bottom. In that case, cooperation is mutually beneficial. Countries should therefore in principle be able to agree on tax policies (although negotiations may of course be more difficult with many countries). Relaxing the assumption of symmetry implies that gains and losses are distributed according to the asymmetries, that is, there are winners and losers. Winners may then have no incentive to cooperate.

We are interested in policy options that improve welfare over the level achieved in the Nash equilibrium in carbon taxes identified in Figure 7. Due to the game structure that emerges in our model of asymmetric tax competition, the resource poor country loses relative to the socially desirable *notax* scenario. Also, the resource rich country does not gain much in the Nash equilibrium relative to the *notax* scenario.

We can show in our model how cooperation creates possibilities for Pareto-improvements. Similar to symmetric tax competition, negotiations could produce a Pareto improvement when governments agree on any point in the quadrant upwards and to the right

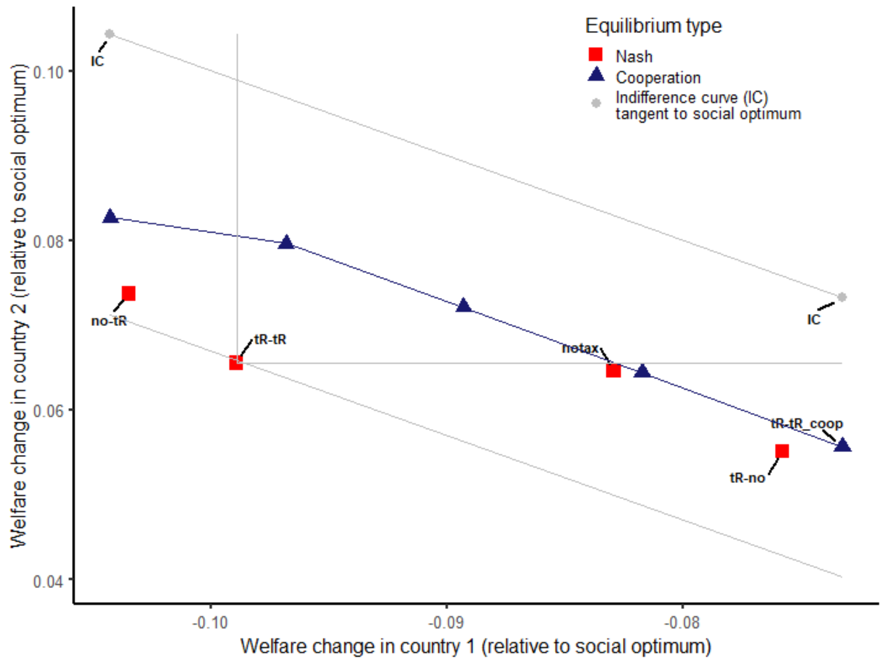

Figure 8: The Pareto frontier for cooperative implementations of the carbon tax in both countries is shown as dark blue line connecting the triangles.

of the tR-tR point in Figure 8. When restricted to using only carbon taxes (that is, other instruments like direct transfers or other taxes are not available), the intersection of this quadrant with the Pareto frontier of the cooperative solution defines the possible Pareto-improvements (blue line connecting the triangles). As shown in the figure, in our benchmark calibration, this leads to BGE welfare improvements around the order of magnitude of 1%. Other solutions with possibly higher social welfare would require further instruments, such as compensation payments. Such Pareto improvements are always possible, independent from the degree of asymmetry in resource endowments, as we will demonstrate in Section 6.1.
We summarize our results in the following.

Proposition 4. *The cooperative solution differs from the solution of the social planner because the social planner has much more freedom to allocate goods and factors than the two governments. In particular, the latter are constrained by the profit maximizing behavior of the resource extracting firms in the two countries, who both operate under convex extraction costs, while the planner is not.*

Proposition 5. *The pay-off structure of a game between the two asymmetric players with the two strategies to either set the carbon tax to zero or to chose the unilaterally optimal tax path is very similar to that of a Prisoner's Dilemma.*

Corollary 1. *Pareto improvements over the Nash equilibrium are possible. In our benchmark calibration, welfare in each country could be increased by one percent. That is, it would be possible to raise aggregate consumption once and forever by one percent.*

6. Robustness of results

In the following, we demonstrate to what extent the results we have presented above are robust with respect to different changes in the assumptions underlying our modeling

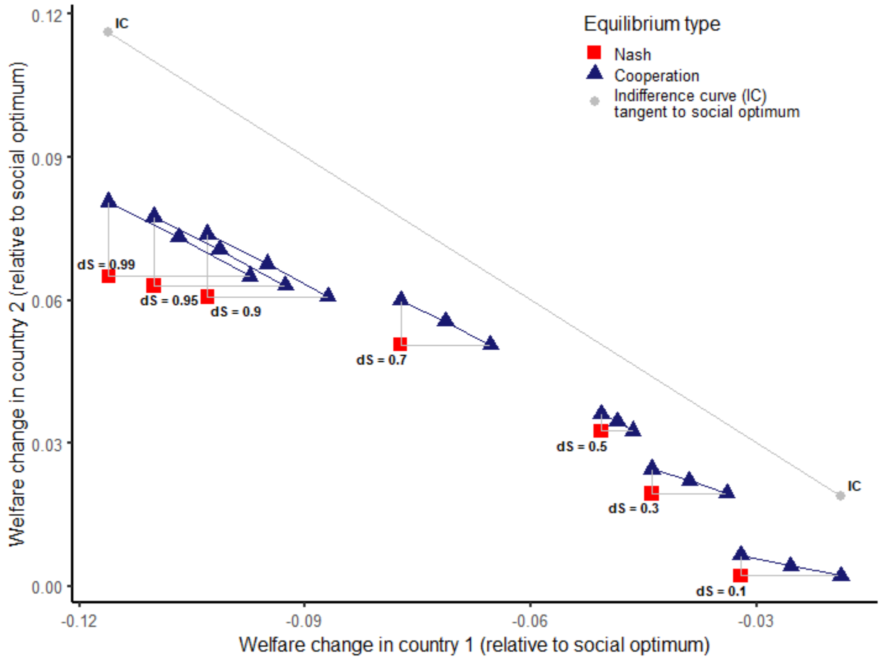

Figure 9: Welfare losses relative to the respective social optimum for varying degrees of asymmetry in resource endowments.

approach. We begin by demonstrating that the possibility for Pareto improvements is robust under variations of the the degree of asymmetry in resource endowments. In Section 6.2, we continue with a sensitivity analysis of other central parameters. Then, in Section 6.3, we illustrate the implications of including capital taxes in the analysis. It turns out that making capital taxes available to the governments does not change the basic insights we've gained from the above analysis in which we've abstracted from capital taxation.

6.1. Sensitivity to degree of asymmetry in resource endowments

In Figure 9, we show a variation of the shares of the total stock of global fossil resources that the two countries own. The parameter $\mathrm{dS} \in [0, 1]$ determines the degree of asymmetry in resource endowments between the two countries. The shares s_j, $j = 1, 2$ of the two countries depend on it according to

$$s_j = \frac{1}{2}(1 - \mathrm{dS}) + (j - 1)\mathrm{dS}. \tag{26}$$

For $\mathrm{dS} = 0$, the countries are symmetric and $s_1 = s_2 = \frac{1}{2}$. Increasing dS above zero shifts resource endowments towards country $j = 2$, up to the extreme case in which $\mathrm{dS} = 1$, implying that $s_1 = 0$ and $s_2 = 1$. We only consider policy scenarios in which both countries' governments set carbon taxes optimally. Squares indicate Nash equilibria in which the two countries' governments set carbon taxes non-cooperatively, triangles are cooperative equilibria.

Figure 9 shows that in all cases a Pareto improvement beyond the inferior Nash equilibrium (red squares) is possible. The dark blue triangles indicate equilibria that can be achieved by cooperation. Independent of the degree of asymmetry in resource endowments, cooperating governments can jointly implement carbon taxation in such a way that both countries are made better off.

dS	Scenario		$\tau_{R,1}$ (NPV)	$\tau_{R,2}$ (NPV)	$\tau_{R,1}$ (rate)	$\tau_{R,2}$ (rate)	taming effect
0.9	τ_R - no	K mobile	145	0	396	0	yes
		K immobile	157	0	542	0	
	no - τ_R	K mobile	0	-294	0	-526	yes
		K immobile	0	-425	0	-827	
0.7	τ_R - no	K mobile	119	0	318	0	yes
		K immobile	135	0	415	0	
	no - τ_R	K mobile	0	-208	0	-418	yes
		K immobile	0	-293	0	-555	
0.6	τ_R - no	K mobile	106	0	277	0	yes
		K immobile	114	0	371	0	
	no - τ_R	K mobile	0	-172	0	-362	yes
		K immobile	0	-249	0	-498	
0.55	τ_R - no	K mobile	99	0	257	0	yes
		K immobile	111	0	352	0	
	no - τ_R	K mobile	0	-155	0	-334	yes
		K immobile	0	-213	0	-434	
0.5	τ_R - no	K mobile	92	0	235	0	no
		K immobile	85	0	167	0	
	no - τ_R	K mobile	0	-139	0	-307	no
		K immobile	0	-144	0	57	
0.3	τ_R - no	K mobile	60	0	151	0	no
		K immobile	13	0	4	0	
	no - τ_R	K mobile	0	-303	0	-109	no
		K immobile	0	-81	0	-201	
0.1	τ_R - no	K mobile	25	0	60	0	no
		K immobile	-32	0	-99	0	
	no - τ_R	K mobile	0	-32	0	-94	yes
		K immobile	0	-317	0	-149	

Table 5: Net present value of carbon tax revenues [tril. US$] and average carbon tax rate [$/tC] for different policy scenarios under variation of dS, the degree of asymmetry in endowments with fossil resources. The last column indicates whether allowing for capital mobility has a taming effect.

Moreover, we have also tested the robustness of Proposition 3 under variation of the shares of the total stock of global fossil resources. In Table 5, we report average carbon tax rates and revenues. It turns out that the Proposition is valid for high degrees of asymmetry in resource endowments. For parameter values of dS > 0.5, that is, if the resource rich country is assumed to own more than 75% of the global fossil resource stock, capital mobility has the taming effect.

6.2. Sensitivity to other model parameters

We have conducted one-at-a-time variations of all model parameters. Here, we describe only those variations of parameters to which our model is sensitive. Variations of the parameters that we have left out here do not change our results qualitatively nor quantitatively to a significant extent.

We find that the game structure that emerges is sensitive with respect to certain parameters (α_1, α_3, $A_{L,0}$, η, $\gamma_{L,0}$, ρ, χ_3). Compared to the benchmark calibration of our model, variations of these parameters can lead to the emergence of a true Prisoner's Dilemma game structure (see Section 4 in the appendix for standard values of all param-

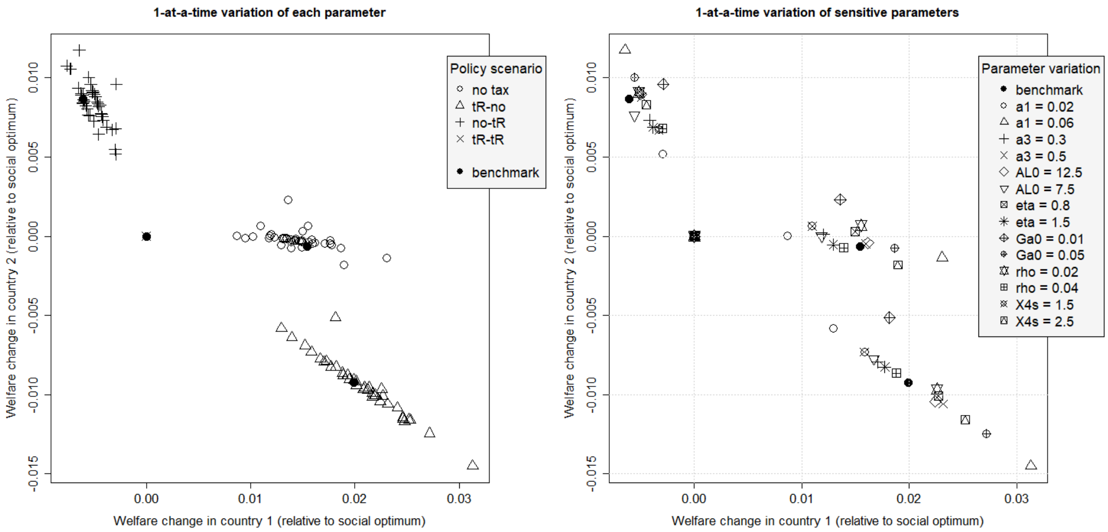

Figure 10: Welfare changes relative to “tR-tR” scenario of the other three policy scenarios. In the left panel, data points show variations including all model parameters. In the right panel, only data points for those parameters to which the game structure is sensitive are shown.

Scenario		$\tau_{R,1}$ (NPV)	$\tau_{R,2}$ (NPV)	$\tau_{R,1}$ (rate)	$\tau_{R,2}$ (rate)
τ_R - no	capital mobile	145	0	396	0
τ_R - no	capital immobile	157	0	542	0
(τ_K, τ_R) - τ_K	capital mobile	145	0	396	0
no - τ_R	capital mobile	0	-294	0	-526
no - τ_R	capital immobile	0	-425	0	-827
τ_K - (τ_K, τ_R)	capital mobile	0	-298	0	-523

Table 6: Net present value of carbon tax revenues [tril. US$] and average carbon tax rate [$/tC] for different policy scenarios under the assumption that the resource poor country (Country 1) owns 5% of all resources and the resource rich country (Country 2) owns 95%. Note that a scenario called ”X - Y” in the first column means that country 1 uses policy instrument(s) X and country 2 uses policy instrument(s) Y.

eters). Instead of the payoffs as displayed in Figure 7, variations of the listed parameters may result in strictly higher payoffs for both countries in the “notax” scenario than in the $\tau_R - \tau_R$ scenario. In Figure 10 we show how variations of all parameters change the game structure (left panel). In the benchmark case, Country 2 slightly prefers the “tR-tR” scenarios over the “notax” scenario. However, variations of the above listed parameters may produce conditions under which both countries prefer the “notax” scenario over the tR-tR scenario. The right panel shows variations for these specific sensitive parameters.

6.3. Availability of capital taxes

In the following, we discuss how the above results change, when in addition to carbon taxes, the two governments can optimize capital taxes as well. By and large, the above results still hold qualitatively and the changes are quantitatively rather small.

For example, Table 6 shows that closing borders to capital movements has a far greater impact than allowing both countries to optimize capital taxes.

Moreover, when governments have access not only to carbon taxes, but may also tax capital, we observe quantitatively small effects that do not change the quasi-Prisoner’s

Dilemma game structure as shown in Figure 7. In Figure 11 we show how the game structure depicted above changes. Deviations from the equilibria without availability of capital taxes are minor.

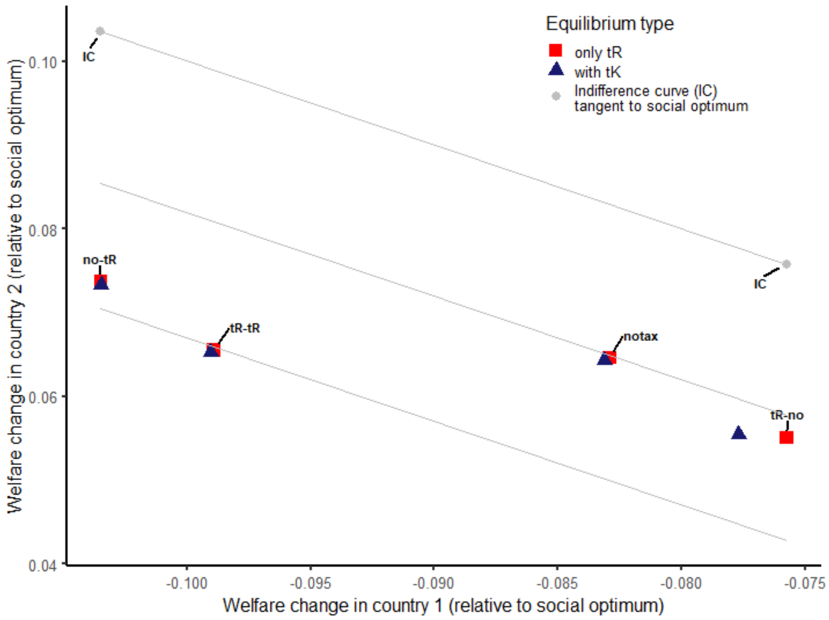

Figure 11: Nash equilibria for different policy instrument portfolios.

7. Extensions

In this section, we explore three extensions of the standard model presented above. The first two extensions aim to clarify how our findings relate to the distinction of models of tax competition and optimal taxation and retaliation (tariff wars). The third extension is motivated by the introduction of the global minimum tax on capital in 2021. We introduce such a minimum tax on capital in our model and calculate both cooperative and non-cooperative equilibria.

Models of tax competition go back to the early contributions of Zodrow and Mieszkowski (1986) and Wilson (1986). Typically, tax competition models explore a Nash equilibrium in national tax policies, and explore the tension of a regulator to fund public expenditure with taxes that may cause capital flight (Wilson, 1999). In a majority of contributions public expenditure goes towards local public good provision. Later studies have also assumed fixed government budgets (Peralta and van Ypersele, 2005), or lump-sum revenue recycling (Ogawa, 2013), as well as maximization of revenues or government expenditure (Haufler and Stähler, 2013), to study the implications of fiscal competition in isolation, or explore regulatory competition in a political economy setting, respectively.

It is well known that taxes on production factors can serve as imperfect substitutes for tariffs to improve a country's terms of trade (Friedlaender and Vandendorpe, 1968). Fiscal motives, however, are usually not considered in models of optimal tariffs and retaliation. Optimal tariff models, like tax competition models, frequently analyse regulators in a Nash equilibrium. Rather than taxing factors of production, the focus is typically on border tariffs. The seminal contribution by Kennan and Riezman (1988) finds that in this setting, large countries are the beneficiaries of the strategic interaction ("win the tariff war"). A subsequent study has confirmed this result (Syropoulos, 2002) but model extensions can trigger a reversal of this finding, by consumption requirements (Kilolo, 2018) or a three country setting (Kreinin et al., 1996).

Our analysis finds "large" countries to benefit from fiscal competition – in contrast to previous tax competition studies but in line with some of the literature on tariffs and retaliation.[14]

Two extensions of our base model shed some light on this distinction. First, we introduce public infrastructure as a local public good. This strengthens the motives for taxation in our model and moves our setting further towards the core tax competition literature. Second, we briefly connect to the studies of optimal tariffs by replacing factor taxes by border tariffs for resources and capital in our model.

We find, first, that our main results remain unchanged in the model extension by public good provision. Second, border tariffs behave qualitatively very similar to factor taxes but their effect on welfare is substantially stronger.

7.1. Infrastructure

In the above model setup, we departed from standard assumptions by abstracting from public goods provision. Governments used tax revenues only as lump-sum transfers, and they financed subsidies on factors by lump-sum taxes. Here, we relax that assumption by including publicly provided infrastructure G as an additional input factor in production. Our main insight is that the results we obtained above using the model without infrastructure remain robust under inclusion of this new feature.

To include infrastructure, we add an additional nest to the CES production function (12) of the final goods sector. Production, thus, is described by the following equations.

$$F(K_t^d, G_t, L_t, R_t^d) = \left[\alpha_1 (A_{R,t} R_t^d)^{s_1} + (1-\alpha_1)\mathbf{X}(Z_t, L_t)^{s_1}\right]^{\frac{1}{s_1}} \qquad (12')$$

$$\text{where} \qquad \mathbf{X}(Z_t, L_t) = \left[\alpha_2 Z_t^{s_2} + (1-\alpha_2)(A_{L,t} L_t)^{s_2}\right]^{\frac{1}{s_2}}$$

$$Z_t = Z(K_t^d, G_t) = \left[\alpha_3 (K_t^d)^{s_2} + (1-\alpha_3) G^{s_3}\right]^{\frac{1}{s_3}}$$

The national infrastructure stock depreciates with the same rate δ as private capital. It evolves according to

$$G_{t+1} = G_t(1-\delta) + T_t^I$$

where T^I are governmental infrastructure investments. A national government's budget equation is now given by

$$\tau_{R,t} R_t = T_t^I + \Gamma_t$$

With this extension, governments now have the additional degree of freedom to choose between spending tax revenues on lump-sum transfers Γ and on infrastructure investments T^I. We restrict transfers and infrastructure investments to be non-negative.[15]

[14] We are grateful to Jay Wilson for pointing out these parallels. The analysis in these extensions are motivated by this observation.

[15] Otherwise, governments would simply implement a negative lump-sum transfer, that is, a lump-sum tax to finance infrastructure optimally. They would then use the carbon tax under the same strategic

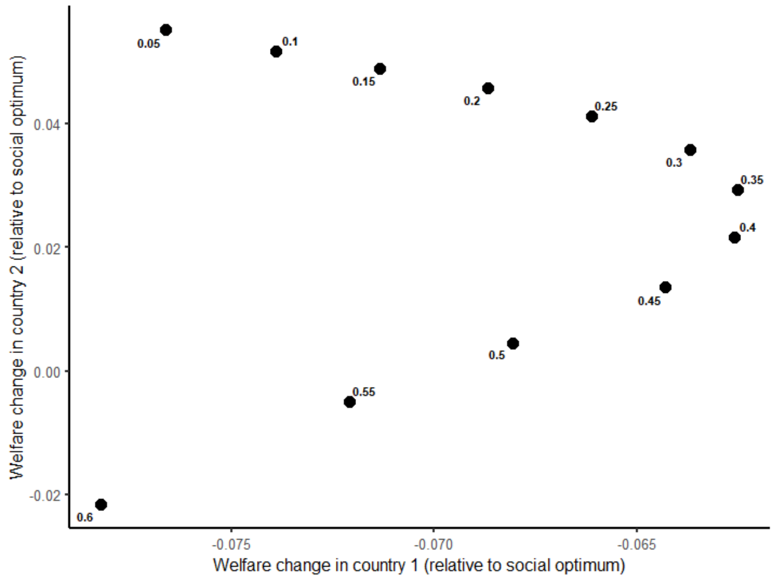

Figure 12: Data points show Nash equilibria when both countries use the carbon tax to finance infrastructure investments. The coordinates give the BGE welfare change (relative to social optimum) of both countries for a variation of $(1-\alpha_3)$, the infrastructure share parameter in production function (12'). Data labels indicate the value of the infrastructure share parameters.

Governments' strategies now include control variables both on the income side and on the spending side of fiscal policy. They choose the carbon tax rate as well as how to divide tax revenues among investments and transfers. For the latter, we introduce the investment rate $\frac{T^I}{\tau_R R}$ as policy instrument, which is necessary to ensure the functioning of our solution algorithm (see Appendix Appendix B).

We have the following insights.

1. The "small", that is, the resource poor country is worse off than the "big" resource rich country in all cases considered. This is independent of the share parameter of infrastructure, $(1-\alpha_3)$, a measure of how important infrastructure is final goods production (see Figure 12).
2. The incentives of the resource poor and rich countries to tax domestic use of fossil resources remain as shown in Section 5.1. The resource poor country implements higher taxes than the resource rich country in order to appropriate the resource rent (see Figure 13).
3. Pareto improvements over the Nash equilibrium are possible when governments cooperate in setting carbon tax rates (see Figure 14).

7.2. Trade policy instruments

The main focus of this paper is to analyze how domestic policies affect international markets. The carbon and capital taxes, which we considered above, did not distinguish between domestically produced and imported fossil resources and capital. However, governments are aware of the international effects of their choices. Therefore, we now extend the analysis to dedicated trade-policy instruments, that is, import tariffs and export duties on the markets for capital and fossil resources, respectively. We continue to

considerations already described by our standard model without infrastructure and nothing new could be learned by including the latter.

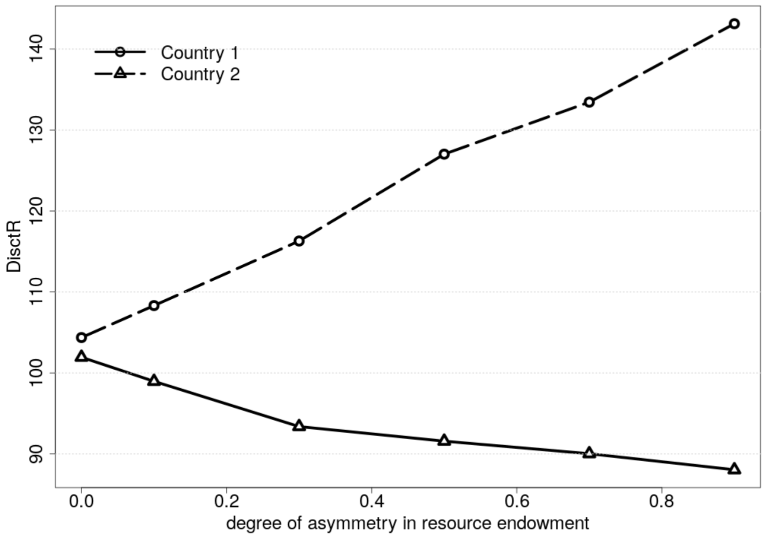

Figure 13: Net present value (NPV) of carbon tax revenues in each country [10^{12} US$] as function of the degree of asymmetry in resource endowments. With increasing asymmetry in resource endowments (x-axis), the incentives of the resource poor country (Country 1) and the resource rich country (Country 2) to tax the domestic use of fossil resource diverge.

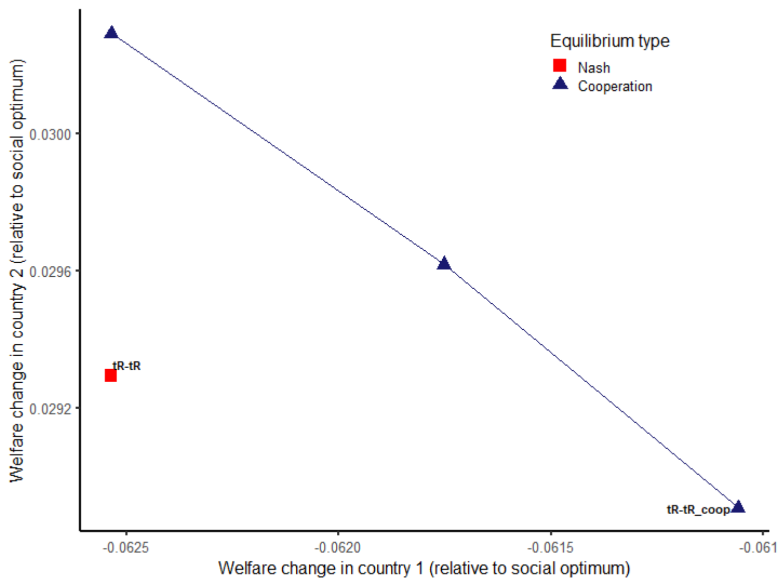

Figure 14: BGE welfare change (relative to social optimum) of both countries. The Pareto frontier for cooperative implementations of the carbon tax in both countries is shown as dark blue line connecting the triangles.

assume that Country 1 is resource poor and holds only 5% of all fossil resources in the economy and Country 2 holds 95%. Due to diminishing marginal productivity of input factors, Country 1 imports resources and exports capital and Country 2 vice versa.

The main result is that governments in most cases prefer trade policy instruments (import tariffs and export duties) to the more general domestic policies (capital and carbon taxes). Our findings can be summarized as follows. For more details, see Appendix Appendix C.5.

We find that the resource rich country strongly benefits from the availability of an export duty for fossil resources. They yield a welfare improvement of more than ten percentage points for the resource rich country – but also imply a welfare loss of twenty percentage points for the resource poor country. The differences in our standard model with capital and carbon taxes are about one order of magnitude smaller. By comparison, the availability of an import tariff on fossil resources improves welfare only very little for the resource poor country.

To include trade policy instruments on the capital market, we extend the model by a representative bank in each country. Since the resource poor country (Country 1) has abundant capital, without any dedicated trade policy, it exports capital to the resource rich country (Country 2). Policy analysis of trade instruments on the capital market reveals that they have a much smaller impact than the instruments on the resource market – one order of magnitude smaller, that is, relative welfare changes are only around one percentage point for both countries.

7.3. Global minimum tax on capital

On October 8th 2021, 137 member countries of the OECD and G20 agreed on a global minimum tax on capital of 15%. We find that implementing such a minimum capital tax in a world where governments set taxes non-cooperatively, the resource poor country reduces its average carbon tax rate, and the resource rich country increases its subsidy. When governments set taxes cooperatively, the minimum capital tax leads to a reduction of carbon taxes. In Table 7, we list average carbon tax rates for cooperative and non-cooperative scenarios for different values of the minimum capital tax, $\bar{\tau_K} \in \{0, 0.05, ..., 0.3\}$.

Setting minimum capital tax rates has only very limited implications for social welfare. The welfare change compared to scenarios without a lower bound on the capital tax never exceeds one percentage point for values of $\bar{\tau_K}$ between 0 and 30%. For example, if governments set taxes non-cooperatively, then for a minimum capital tax of 15%, social welfare changes by 0.2% and 0.02% in the resource poor and the resource rich country, respectively. In the cooperative equilibrium, the change in social welfare is by 0.01% and 0.4% in the resource poor and the resource rich country, respectively.

8. Conclusion

We have discussed the strategic incentives of countries with asymmetric resource endowments, in particular with respect to implementing carbon taxes, when fossil resources and capital are internationally mobile, but labor is not. Our results show that resource poor countries have a tendency to try to appropriate resource rents via the price-channel. Its government will use the carbon tax to depress the producer price, which increases domestic tax revenues, but reduces the foreign resource sector's profits. Resource rich countries have the tendency to try to stop the outflow of fossil resources via

$\bar{\tau_K}$	no	0	0.05	0.1	0.15	0.2	0.25	0.3
$\tau_{R,1}$	295	285	260	232	204	175	152	130
$\tau_{R,2}$	-504	-507	-518	-517	-531	-559	-570	-579
$\tau_{R,1}^{coop}$	254	249	250	241	226	208	191	175
$\tau_{R,2}^{coop}$	244	237	237	225	211	195	178	163

Table 7: Average carbon tax rate [$/tC] for different values of the minimum capital tax $\bar{\tau_K} \in \{0, 0.05, ..., 0.3\}$. We analyze both non-cooperative (upper rows) and cooperative equilibria (lower rows) and we assume that 95% of global fossil resources are held by Country 2.

$\bar{\tau_K}$	0	0.05	0.1	0.15	0.2	0.25	0.3
W_1	-0.0002	-0,0010	-0,0006	-0,0024	-0,0063	-0,0086	-0,011
W_2	0,0003	0,0008	0,0004	0,0002	0,0001	-0,0009	-0,0021
$\tau_{R,1}$	-0.035	-0.12	-0.21	-0.31	-0.41	-0.49	-0.56
$\tau_{R,2}$	0.006	0.028	0.027	0.05	0.11	0.13	0.15
W_1^{coop}	0,0002	0,0009	0,0007	0,0001	-0,0014	-0,0032	-0,0051
W_2^{coop}	-0,0002	0,0013	-0,0022	-0,004	-0,005	-0,0062	-0,008
$\tau_{R,1}^{coop}$	-0,02	-0,02	-0,05	-0,11	-0,18	-0,25	-0,31
$\tau_{R,2}^{coop}$	-0,03	-0,03	-0,08	-0,13	-0,20	-0,27	-0,33

Table 8: Relative change of social welfare W_j (BGE) and the average carbon tax rate $\tau_{R,j}$ under a minimum capital tax $\bar{\tau_K} \in \{0, 0.05, ..., 0.3\}$ compared to the scenario with no lower bound on the capital tax. We analyze both non-cooperative (upper rows) and cooperative equilibria (lower rows) and we assume that 95% of global fossil resources are held by Country 2.

the factor channel. By subsidizing the use of fossil fuels, they attract foreign capital and thus aim at increasing their national income, in particular labor income. Capital mobility has a dampening effect on the incentives of both resource rich and poor countries. Both carbon taxes and subsidies are lower if capital is mobile, compared to scenarios without capital mobility. In particular our result that capital mobility leads to lower carbon taxes in resource poor countries rationalizes the empirical observations related to the pollution haven hypothesis: An increase in trade-openness leads to a reduction of the stringency of domestic environmental regulation (Kim and Lin, 2022). However, these authors also discuss a channel along which an opposing effect may occur, which is related to the Porter Hypothesis. Trade openness may make innovation toward clean and energy- efficient technology desirable since it reduces costs. Hence, trade openness may also stimulate stricter environmental policy. Our model abstracts from differences in (production) technology as well as endogenous technological change. Hence, we have effectively muted this latter channel. This opens a promising avenue for future research, in which the determinants of the balance between the former and the latter channel could be explored.

We have also shown that including internationally tradable fossil resources changes the game structure found by Bucovetsky (1991) and Wilson (1991) for tax competition with asymmetric countries in terms of population size and equal capital endowments per capita. Thereby, we can further conclude that cooperation in carbon taxes can in fact lead to Pareto improvements. With asymmetric resource endowments, non-negligible welfare improvements are possible when governments set their carbon taxes and subsidies cooperatively. Finance ministers might thus be motivated to coordinate environmental policies simply for reasons of correcting pecuniary and fiscal externalities. Therefore, the recent political momentum around the global minimum corporate tax rate might extend to a discussion around a global minimum carbon tax.

Typical studies of carbon taxation are concerned with the Pigouvian motive to tax. We have omitted this features in the present paper to focus exclusively on the strategic incentives involved in fiscal and trade policy. A promising avenue for future research would be to include environmental concerns. This would link the topic of international tax competition to the theory of coalition formation and the strategic provision of global public goods. Moreover, future research could also investigate the implications of altering the structure of strategic decisions such that governments decide their policies simultaneously with the private actors' actions or private actors are the Stackelberg leaders.

Digital supplementary material

The model code is available at https://ars.els-cdn.com/content/image/1-s2.0-S0301420723003240-mmc1.zip

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Appendix A. Calculation of balanced growth equivalents (BGE)

Given the welfare levels achieved in the policy scenario W_{pol} and the social optimum W_{so}, we calculate the BGE welfare loss by comparing those consumption time paths that differ in initial consumption levels C_{pol} and C_{so}, but share a common growth rate γ such that they yield the respective welfare levels W_{pol} and W_{so}:

$$W_{pol} = \sum_{t}^{T} U(C_{pol}(1+\gamma)^t / L_t) \tag{A.1}$$

$$W_{so} = \sum_{t}^{T} U(C_{so}(1+\gamma)^t / L_t). \tag{A.2}$$

Then, the BGE welfare loss is defined as $1 - \frac{C_{pol}}{C_{so}}$. It specifies the once-and-forall loss of consumption that is caused by changing from the socially optimal path to a policy path.

Appendix B. Solution algorithm

To find the equilibrium, we use the following algorithm (see also Franks et al., 2017; Schwerhoff and Franks, 2018):

until policy instruments $\{\tau_{K\,j,t}, \tau_{R\,j,t}\}_{j,t}$ *converge*
repeat for each player j*:*
    unfix policy variables $\{\tau_{K\,j,t}, \tau_{R\,j,t}\}_{j,t}$
    optimize player j*'s payoff/welfare* W_j
    fix player j*'s newly found policy variables* $\{\tau_{K\,j,t}, \tau_{R\,j,t}\}_{j,t}$

We solve the game in which the governments are involved for the open-loop Stackelberg equilibrium (OLSE). In general, an OLSE is not time consistent and some form of closed loop equilibrium would be preferable, although computationally very challenging for the present model due to its complexity involving the two sub-games a) between the two governments and b) between each government and the Stackelberg followers (firms, households, resource extracting firms).

In order to check whether time-inconsistencies can arise, Franks et al. (2017) have tested the solution algorithm by calculating the paths of capital and carbon tax for two standard benchmark cases. Then, they used the model again to calculate the results for the same cases, but fixed the values of the respective tax rates in the first n time periods to those values that they had found in the benchmark cases. Then, they compared the benchmark tax paths with the newly computed paths. In the case of the carbon tax, the governments did not deviate at all from the announced tax path, while with the capital tax only negligibly small deviations could be observed.

While this does not constitute a proof of time-consistency of the model, it still indicates that our approach can be seen as a reasonable first estimation. It is left for further research to develop an algorithm with which a closed-loop Stackelberg equilibrium can be computed.

Appendix C. Additional material

Appendix C.1. Rent appropriation

In Figure Appendix C.1 we compare average prices and quantities on the market for fossil resources to explain how we understand the appropriation of resource rents referred to in Section 5.1. Here, we only consider the quantity of resources sold to the firm in the resource poor country. The numbers are based on our standard calibration. The red squares show the quantity R_1 sold in the scenario without any government intervention, resulting in price p_0. The yellow triangles indicate quantity and prices for the scenario in which the resource poor country can implement a carbon tax and the resource rich country's government does not implement any policy instrument. In the latter scenario, the net-of-tax price on the international market is reduced to $\tilde{p}$. The firm in the resource poor country, however, has to pay the gross price $\tilde{p}+\tau_R$ and thus demands the quantity $\tilde{R}_1$. Since both the net-of-tax price and the quantity sold are reduced under the carbon tax, profits of the resource owners are reduced (note, however, that extraction costs are not diplayed in the diagram). The resource rent that the resource exporting country can retain is thus reduced. By taxing the use of resources, the government in the resource poor country can appropriate part of the resource rent. The portion of the resource rent appropriated corresponds to the small vertically hatched rectangle in the diagram. While total tax revenues in the resouce poor country are made up of both the vertically and the horizontally hatched rectangles, the latter corresponds simply to the consumer surplus of the resource buying firm.

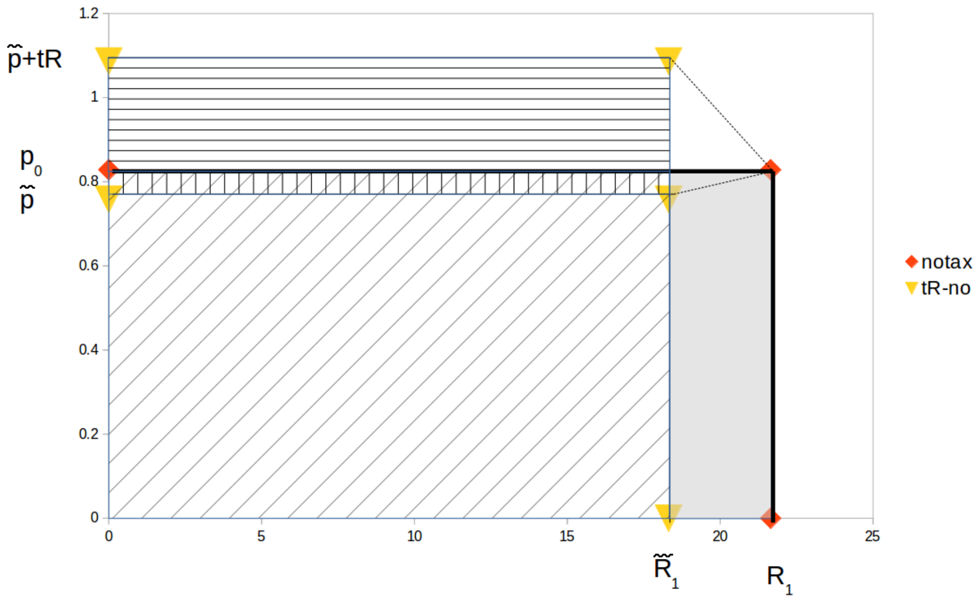

Figure Appendix C.1: Comparison of prices and quantities in the scenarios with a) no taxes, and b) the Nash equilibrium with only the resource poor country implementing its optimal carbon tax.

Appendix C.2. Movement of production factors with varying carbon tax

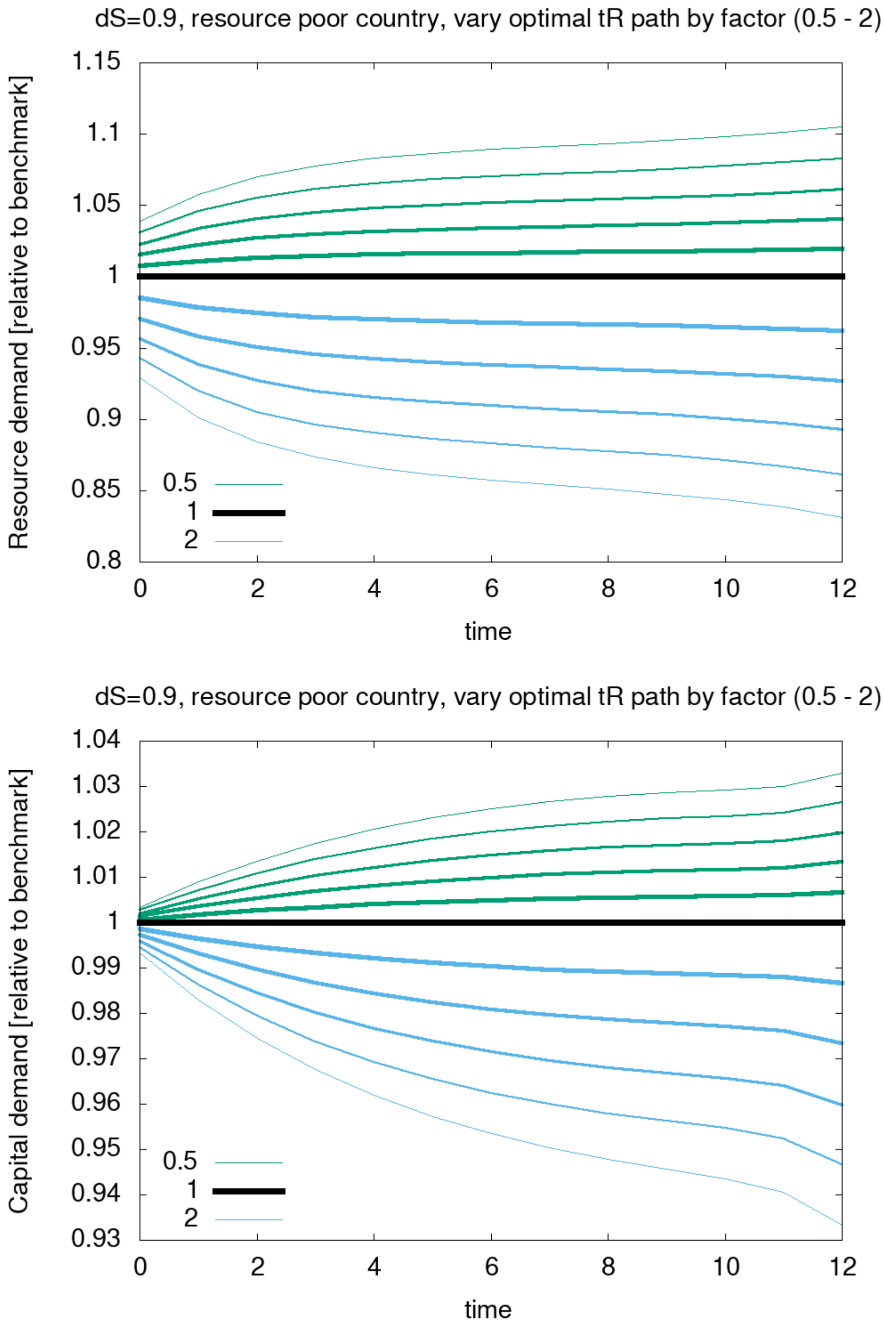

Figure Appendix C.2: Exogenous variation of the optimal carbon tax path the resource poor country choses if the resource rich country does not use any taxes: We show the impact on the demand for capital and resources in the resource poor country (cf. Section 5.1).

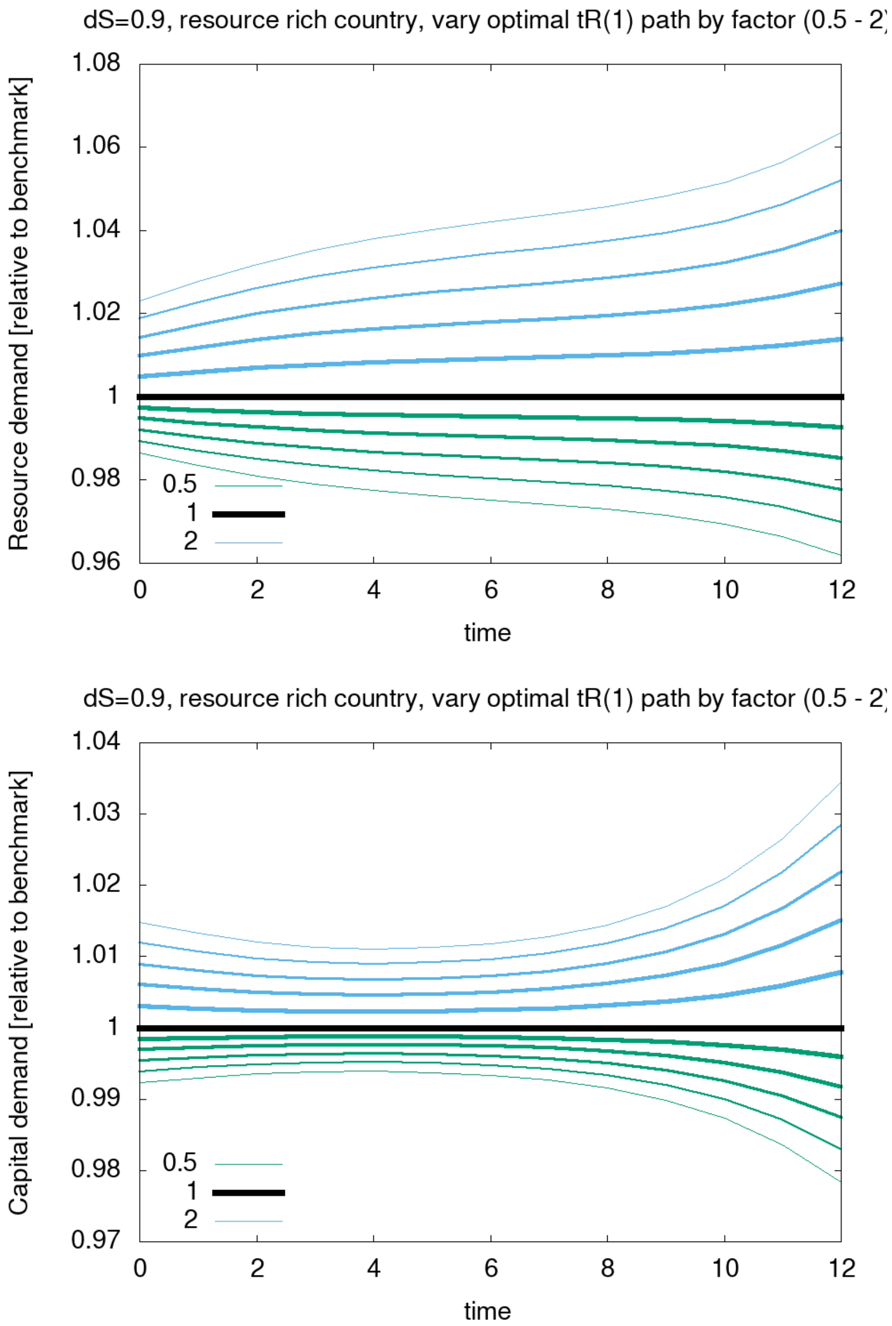

Figure Appendix C.3: For the same scenarios as in Figure Appendix C.2, the plots demonstrate the inflow in the resource rich country if the resource poor country increases its carbon tax (cf. Section 5.1).

Appendix C.3. Pareto frontier

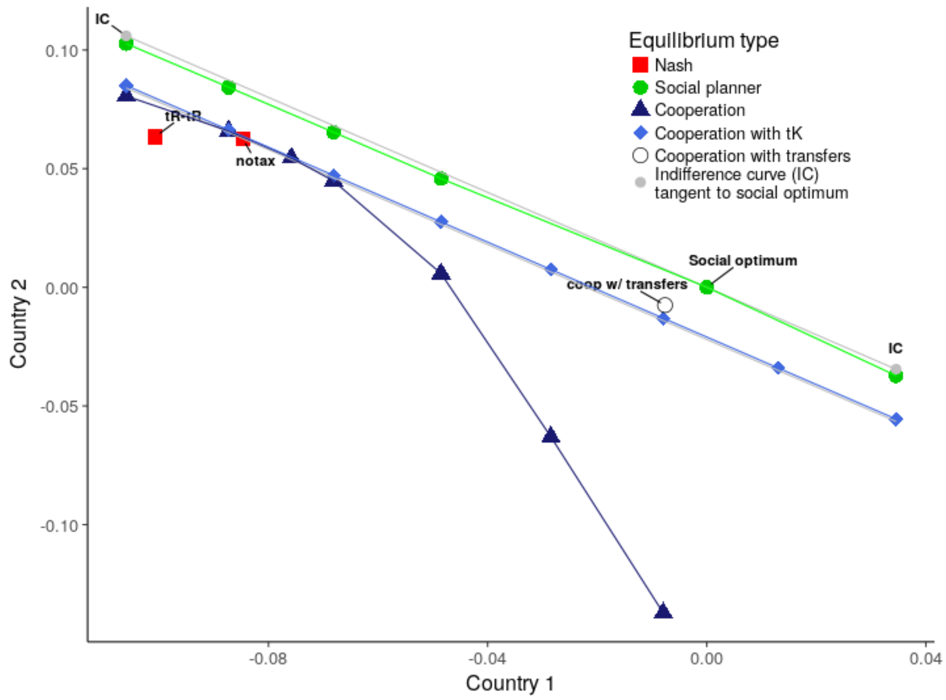

Figure Appendix C.4: Welfare in Country 1 (resource poor) and Country 2 (resource rich) for different allocations a social planner can achieve, and for different allocations attainable by governments implementing policy instruments in both countries cooperatively. Policy instrument portfolios analyzed here are a) carbon taxes (dark blue triangles), b) carbon taxes and capital taxes (light blue diamonds), c) carbon taxes and direct cash transfers (empty circle).

Appendix C.4. Variation of extraction costs

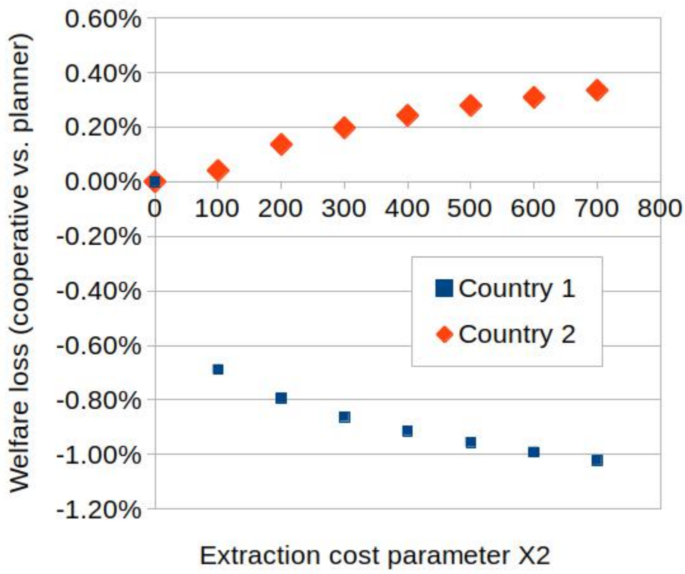

Figure Appendix C.5: If extraction costs are zero, i.e. $\chi_2 = 0$, the (decentral) cooperative solution and the (centralized) social planner solution coincide. As extraction costs increase to our standart calibration, $\chi_2 = 700$, the two cooperating governments are less and less able to achieve the first best outcome.

Appendix C.5. Trade policy instruments

The main focus of this paper is to analyze how domestic policies affect international markets. The carbon and capital taxes, which we considered above, did not distinguish between domestically produced and imported fossil resources and capital. However, governments are aware of the international effects of their choices. Therefore, we now extend the analysis to dedicated trade-policy instruments, that is, import tariffs and export duties on the markets for capital and fossil resources, respectively. We continue to assume that Country 1 is resource poor and holds only 5% of all fossil resources in the economy and Country 2 holds 95%. Due to diminishing marginal productivity of input factors, Country 1 imports resources and exports capital and Country 2 vice versa. The main result here is that governments in most cases prefer trade policy instruments (import tariffs and export duties) to the more general domestic policies (capital and carbon taxes). We first analyze the resource market and then the capital market in greater detail.

Appendix C.5.1. Import tariff and export duty for fossil resources

To include tariffs and duties on fossil resources in our model, we extend each national economy by a representative intermediate firm, which we shall call the fossil resource trader. The resource trader represents a large number of profit maximizing price takers. In each period, the trader in the resource poor country (Country 1) buys a quantity $R^s_{1,t}$ of fossil resources on the domestic resource market from the domestic resource extracting sector at its producer price $p^p_{1,t}$ and a quantity $R^{export}_{2,t}$ from the trader in the resource rich country at the trader's price $p^T_{2,t}$ and possibly an import tariff $tar_{1,t}$. The trader in country 1 then pools all resources and sells the quantity $R^d_{1,t} = R^s_{1,t} + R^{export}_{2,t}$ to the final goods producing firm in that country at the consumer price $p^c_{1,t}$. For the trader in country 2, analogous relations hold, except that instead of an import tariff, the trader faces an export duty $d_{2,t}$. Tariffs and duties may become negative and hence turn into subsidies. The trader's profits are given by

$$\pi^T_{1,t} = p^c_{1,t}R^d_{1,t} - (p^T_{2,t} + tar_{1,t})R^{export}_{2,t} - p^p_{1,t}R^s_{1,t}$$
$$\pi^T_{2,t} = p^c_{2,t}R^d_{2,t} + (p^T_{2,t} - d_{2,t})R^{export}_{2,t} - p^p_{2,t}R^s_{1,t}$$

We assume that resource markets clear.

$$R^d_{1,t} = R^s_{1,t} + R^{export}_{2,t}$$
$$R^d_{2,t} = R^s_{2,t} - R^{export}_{2,t}$$

Maximizing traders' profits yields the following first-order conditions.

$$p^c_{j,t} = p^p_{j,t}, \quad j = 1,2$$
$$p^c_{1,t} = p^T_{2,t} + tar_{1,t}$$
$$p^c_{2,t} = p^T_{2,t} - d_{2,t}$$

Hence, by eliminating the trader's price, we obtain a rule that determines the wedge that tariff and duty drive between resource prices in the two countries. It replaces equation (4).

$$p_{1,t} = p_{2,t} + tar_{1,t} + d_{2,t} \quad (4')$$

We find that the resource rich country strongly benefits from the availability of an export duty. In Figure Appendix C.6, the strong impact of allowing Country 2 to set optimal export duties on welfare becomes visible. They yield a welfare improvement of more than ten percentage points (measures in BGE) for the resource rich country – but also imply a welfare loss of twenty

Scenario	NPV of investments in Country 2 absolute [10^{12} US$]	relative planner
no - tR	615	1.26
no - dutR	416	0.85
planner	489	-

Table Appendix C.1: Comparison of the net present value (NPV) of investment in the resource rich country (Country 2) between two policy scenarios and the social planner solution. If Country 2 optimizes only the broad based subsidy to prevent factors from leaving the national economy, there is a substantial overinvestment of 26 percentage points above the level in the social optimum. If it optimizes the export duty, there is underinvestment, but only 15 percentage points below the social optimum.

percentage points for the resource poor country. The differences in our standard model with capital and carbon taxes are about one order of magnitude smaller. Why does the duty perform so much better for the resource rich country? Its government uses the export duty to prevent resources from flowing out of the country. In doing so, it distorts (a) the allocation of capital between resource extraction and final goods production, and (b) the intertemporal savings decision of domestic households much less than a broad based domestic subsidy on fossil resource use (as discussed in Section 5.1.2). To illustrate the magnitude of the distortion on the domestic capital market, we compare the net present value of investments for two policy scenarios and the first best optimal solution a social planner would implement in Table Appendix C.1. By comparison, the availability of an import tariff improves welfare only very little for the resource poor country. In some cases, it even makes the resource poor country worse off, as for example in the scenarios "tarR-tR" vs. "no-tR" and "tarR-dutR" vs. "no-dutR".

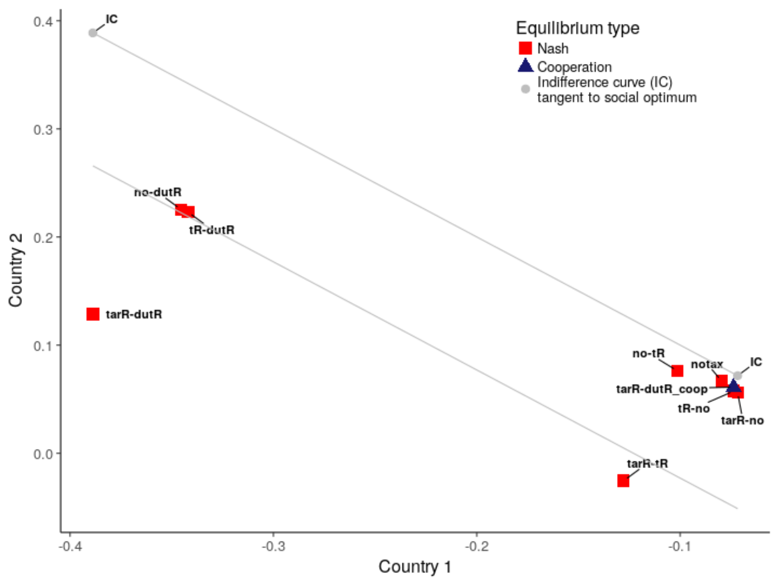

Figure Appendix C.6: BGE Welfare change (relative to social optimum) for different combinations of trade policy instruments on the market for fossil resources.

Appendix C.5.2. Capital tariffs and duties

In analogy to the resource market, trade policy instruments on the capital market can be analyzed in our model. These instrument have a much smaller impact than the instruments on the resource market, about one order of magnitude smaller. Relative welfare changes are only around one percentage point for both countries. This is consistent with our findings on capital taxes in Section 6.3, which also have only minor impacts compared to national carbon taxes.

Moreover, we find that both countries typically prefer their respective trade policy instruments to domestic taxes or subsidies on the total capital stock. Analogously to the trade policy instruments on the resource market, tariffs and duties on the capital market have a smaller ”tax base” and cause less severe distortions.