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The Green Paradox and Interjurisdictional Competition across Space and Time*

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Abstract: This paper demonstrates that unintended effects of climate policies (Green Paradox effects) also arise in general equilibrium when countries compete for mobile factors of production (capital and resources/energy). Second, it shows that countries have a rationale to use strictly positive source-based capital taxes to slow down resource extraction. Notably, this result comes about in the absence of any revenue requirements by the government, and independently of the elasticity of substitution between capital and resources in production. Third, the paper generalizes the results obtained by Eichner and Runkel (2012) by showing that the Nash equilibrium entails inefficiently high pollution.

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1 Introduction

Climate policies which curb the demand for fossil resources like coal, oil and natural gas have been met with skepticism in the last couple of years. For one thing, they have not been successful in reducing emissions from the burning of fossil fuels significantly, and for another thing, they have been shown to have an unintended effect. In particular, rapidly rising carbon taxes over time may incentivize resource owners to extract more quickly and thereby accelerate climate change. The intuition is that resource owners anticipate that rising future carbon taxes will lower market prices and decrease future resource rents. Therefore, they will extract more resources in the present. This effect has become known as the "Green Paradox" (Sinn, 2008). As a remedy to this unintended effect, Sinn proposes a supply-side policy that is aimed at lowering the returns to resource owners' investment, namely a withholding tax imposed on resource owners' capital gains that lowers the net return on their financial investments and thus makes extraction less attractive.

This early analysis by Sinn neglects two important features that are relevant for climate policy. First, the interest rate at which resource owners can invest their income from extraction is not exogenously given. It is influenced by extraction itself because a change in extraction will lead to a change in capital supply and thus a change in the interest rate. This issue has recently been addressed by Eichner and Pethig (2011) and van der Meijden et al. (2015). The latter authors find that the Green Paradox is likely to happen also in a general equilibrium setting. Second, both capital and resources are mobile factors of production and chase the highest returns internationally. This mechanism provides incentives to governments to influence the allocation of capital and resources in their favor. These strategic considerations by governments are reflected in the design of national tax systems. Evidence of tax competition of this kind are declining statutory corporate income tax (CIT) rates. For example, the average CIT rate in EU countries fell from 35.5% to 24.2% between 1997 and 2007 (KPMG, 2007). Similar trends are observed in resource-rich countries in Sub-Saharan Africa where average rates dropped from 40% in 1980 to 35.4% in 2005 (Keen and Mansour, 2008).

The contribution of this paper is threefold. First, I show that Green Paradox effects also arise in general equilibrium under reasonable assumptions in a world in which countries compete for mobile capital and mobile resources. Second and more importantly, I argue that in such a second-best world, there is indeed a rationale for non-cooperative but welfare-maximizing governments to complement their tax portfolios with policies similar to Sinn's proposed withholding tax on resource owners' capital gains. More specifically, governments have an incentive to tax capital investment at a strictly positive rate and are indeed better off under a regime where capital *and* resource taxes are employed compared to a regime with only resource taxes at their disposal.[1] Third, employing a positive tax on capital investment as an additional instrument does not lead to efficiency. Rather it is shown that decentralized policy-making brings about inefficiently high pollution due to inefficiently high resource extraction in the present. In this regard, the paper generalizes the results obtained by Eichner and Runkel (2012) who show in a two-period model that the efficiency result of Ogawa and Wildasin (2009) does not hold with endogenous capital supply and emissions.

The intuition why governments find it beneficial to employ strictly positive capital taxes in their tax portfolio is that capital and resources are complementary production factors and a future source-based tax on capital in addition to carbon taxes lowers the interest rate (just like Sinn's proposed capital income tax on resource owners' financial assets) through general equilibrium effects and thereby slows down resource extraction. This channel which I will refer to as "capital-tax-interest-rate" channel is stronger the higher is the elasticity of substitution between capital and resources in production. The reason is that with a higher elasticity, an additional capital tax in the future induces a stronger substitution out of capital into resource use in the future, provoking a sharper decline of the interest rate. This fall in the interest rate stimulates future resource demand in all other countries by inducing a fall in the resource price through the Hotelling rule and by making capital use by firms more attractive. Higher investment also increases resource demand due to the assumed complementarity between capital and resources. As a consequence, current resource extraction falls. Remarkably, the open-loop Nash equilibrium when resource taxes and a capital tax are available to governments entails a strictly positive future capital tax in the absence of any revenue requirements by the government and independently of the elasticity of substitution.

This paper models the *interaction* of global capital and resource markets and the *strategic interaction* between jurisdictions (or countries) in attracting mobile factors of production in the presence of an environmental externality that is associated with resource use. I consider jurisdictions which non-cooperatively maximize their residents' lifetime utility by choosing from a set of environmental taxes on resource (energy) use and a source-

[1] While the capital tax in my model is also source-based, it taxes capital investment directly, i.e., on the side of production firms, not on the capital income side of the investing party. In this sense, this tax on capital investment can be considered a demand-side policy. I focus on demand-side policies here because they still seem to rank higher on the political agenda than supply-side policies.

based tax on capital investment. Competitive markets allocate capital and resources across countries and across periods. Resources are assumed to be in finite supply and can be extracted in the first or second period. Governments are interested in the speed of extraction and do not care about fiscal revenues. Particular emphasis in the analysis is devoted to the role that factor mobility and the elasticity of substitution between capital and resources play with respect to the efficiency of decentralized policy-making.

To focus on strategic interactions, I stick with the common approach in the tax competition literature in assuming symmetry between jurisdictions and examining symmetric equilibria (e.g. Zodrow and Mieszkowski, 1986). As pointed out by Schwerhoff and Edenhofer (2013), symmetry eliminates some potentially beneficial effects of capital mobility, in particular any gains from capital trade (and resource trade like in this paper). Furthermore, there exist huge differences in the endowment with fossil oil and gas across countries. These differences are, however, less pronounced for coal. Therefore, symmetry may be a good starting point for analyzing strategic behavior by welfare-maximizing governments.

I find that unilateral increases in resource or capital taxes cause *intra*temporal leakage of resource use and thus emissions but also *inter*temporal leakage. For a positive capital supply elasticity, rising future resource taxes induce higher resource extraction in the present, confirming the Green Paradox result obtained in partial equilibrium. By contrast, rising future capital taxes may either speed up or slow down extraction, depending on the degree of complementarity between capital and resources. For example, if capital and resources can be easily substituted, a marginal increase in the future capital tax leads to a reallocation of production inputs towards the resource in the future and thus decreases resource use in the present. In the absence of resource taxes in the governments' tax portfolio, governments would therefore either tax or subsidize capital investment under commitment. Surprisingly, this ambiguity goes away whenver governments have both capital and resource taxes at their disposal. In that case, strictly positive capital taxes prevail in equilibrium while resource taxes fall over time.

The open-loop Nash equilibrium is found to entail inefficiently high resource use in the present. In addition to the usual free-riding incentives by governments due to the environmental externality, private income externalities arise because capital tax and resource tax bases abroad are affected. These externalities unambiguously aggravate the transfrontier pollution problem.

Although the open-loop Nash equilibrium is time-inconsistent because governments would wish to deviate from their announced policies once the second period arrives, it would be very easy to mimic a positive capital tax in the second period by subsidizing savings in the first period. This policy would also bring the interest rate in the second period down and thus decelerate resource extraction.

2 Related literature

This paper bridges the gap between two literatures: the resource economics literature, which analyzes the *intertemporal* allocation of non-renewable resources, and the literature on tax competition, which is concerned with the *static* allocation of production factors and the efficiency of decentralized policy-making in the presence of interjurisdictional spillovers.

It adds to the latter literature, which originates in Zodrow and Mieszkowski (1986) and Wilson (1986), by introducing a finite stock of resources and allowing for different degrees of complementarity between capital and resources in a general equilibrium framework. One of the first contributions to this strand of literature in the context of environmental policy is Oates and Schwab (1988) who find efficiency of decentralized policy-making if there are no pollution spillovers across jurisdictions and first-best tax instruments are available. Ogawa and Wildasin (2009) confirm this result for the case when capital (which is assumed in fixed supply) and emissions are perfect complements and pollution is transboundary. However, in their model, any tax rate is efficient and thus is the tax rate in the Nash equilibrium. Eichner and Runkel (2012) endogenize capital supply and thus emissions in the same framework and conclude that the Nash equilibrium brings about inefficiently low capital taxes. While the focus of the latter paper is on the role of the capital supply elasticity, this paper is concerned with the role of the elasticity of substitution between capital and resources in production. Withagen and Halsema (2013) also employ a tax competition framework but reverse the conventional timing of decisions such that households anticipate government policies when deciding about savings. They find a potential race to the top in environmental regulation. Rauscher employs similar but static models of interjurisdictional factor mobility. In the case of environmental externalities on utility, capital mobility is found to aggravate transfrontier pollution problems (Rauscher, 1991, 2000, 2005), implying inefficiently lax environmental regulation. By contrast, environmental regulation may be inefficiently strict if emission externalities affect capital productivity (Rauscher, 1997a, 1997b). The whole literature on tax competition has largely ignored intertemporal considerations like in this paper, with a recent exception being Klein and Makris (2014).

The present paper also contributes to the resource economics literature which has mostly focused on single-country models (which can be interpreted as representing the world economy) or comparative static exercises in multi-country models, largely neglecting strategic interaction between countries. Svensson (1984), Marion and Svensson (1984), Elbers and Withagen (1984) and van Wijnbergen (1985) study the welfare effects of oil price increases, of tariffs and subsidies on oil imports and of capital income taxes in models of international trade in the absence of any pollution externalities. Aarrestad (1978) and Farzin (1999) examine the joint determination of optimal savings and resource extraction in a model with an exogenous interest rate and no factor mobility. The rare general equilibrium treatments in this literature include Chiarella (1980), Elbers and Withagen (1984), Hillman and Long (1985) and Golosov et al. (2014). Recently, a new strand has emerged – the literature on the so-called "Green Paradox", a term coined by Sinn (2008), with the idea originating in Sinclair (1992, 1994). It studies the effects of taxes on the equilibrium extraction path of a non-renewable resource. Particularly, the weak version of the Green Paradox states that a greening of future tax policies will induce resource owners to speed up extraction in the present. This paper is most closely related to van der Meijden et al. (2015) who find that the Green Paradox may be mitigated, attenuated or even reversed in general equilibrium, with the most realistic outcome being a weakening of this unintended effect. In this paper, I confirm that Green Paradox effects occur under reasonable assumptions. In addition, I go one step beyond the analysis in van der Meijden et al. (2015) by deriving the Nash equilibrium tax rates on resources and capital under commitment. Further related papers are Eichner and Pethig (2011, 2013) who analyze unilaterally imposed emissions caps in models with two periods and two or three countries but neither include capital as a production input nor an endogenous extraction decision by resource firms. Burniaux and Oliveira Martins (2012) develop a two-region, two-goods general equilibrium framework with international trade and capital mobility to explore carbon leakage of unilaterally imposed policies.

Recently, two papers have addressed these two literatures, as well. Franks et al. (forthcoming) model the strategic interactions between two symmetric resource-importing countries and show that competition over carbon taxes Pareto-dominates competition over capital taxes for these countries because it is able to capture part of the resource owners' scarcity rent. Tax competition in that model is motivated purely by fiscal, not environmental concerns like in my model. Ogawa et al. (2016) show in a static model that while increased capital mobility increases global production efficiency, the gains from capital market integration and capital tax competition accrue only to resource-poor countries.

The papers mentioned above miss out at least one of the following features which are all relevant in the context of climate policy and addressed in the present paper: (1) Non-renewable resources are in finite supply. (2) Their use causes environmental externalities. (3) The economy is not a single unit, and decentralized policy-making implies strategic interactions. (4) Capital and resources are mobile. (5) The interaction of different factor markets requires treatment in a general equilibrium framework.

3 The model

I consider an economy consisting of $n \geq 2$ symmetric jurisdictions which can be thought of as sovereign countries. The time horizon of the model comprises two periods. For simplicity, I shall sometimes refer to period one as 'the present' or 'today' and period two as 'the future' or 'tomorrow'. Governments are the strategic agents in this model and play a Nash game over tax rates, taking the decisions and reactions of all (non-strategic) followers, i.e., households and firms, into account.

The model builds up on Eichner and Runkel (2012) but differs in two important respects. First, I model production not only in one period. This allows me to capture the effect of current climate policies on savings and thus future consumption. Second, I relax the assumption that emissions are tied one-to-one to capital investment by introducing non-renewable resources (such as oil, coal and gas) as an additional and explicit production factor which can be substituted for capital to some degree. Resources are fully exhausted by the end of the time horizon, and their use in production gives rise to transboundary emissions.

3.1 Production firms

In each country i and each period $t = 1, 2$, a representative firm produces an output good which is taken as the numéraire. Firms in all countries have access to the same production technology $F(k_t^i, r_t^i)$ where k_t^i denotes capital input and r_t^i non-renewable resource (or energy) input in period t. Production is increasing in both inputs with decreasing marginal returns ($F_{kk} < 0 < F_k$, $F_{rr} < 0 < F_r$). The cross-partial derivative is assumed to be positive, $F_{kr} > 0$ (though I will sometimes contrast my results with $F_{kr} = 0$ to provide intuition). The higher F_{kr}, the more complementary (or 'cooperative' in the terminology of Svensson, 1984) are capital and resources in production. I further assume that production exhibits decreasing returns to scale with respect to capital and resources, which implies strictly positive profits.[2]

Installed production capacity results from previous capital investment and is thus fixed in the short run. In other words, the stock of capital $\bar{k}$ employed in each country in the first period is exogenously given and immobile. The production function in this period can then simply be written as $F(\bar{k}, r_1^i) \equiv f(r_1^i)$. Second-period capital is rented on a global capital market at the uniform rate ρ while resources are purchased on a global resource market at price p_t in period t.[3]

Given that country i levies a unit source-based tax κ^i on capital[4] and a period-specific (resource or environmental) tax τ_t^i on resource use, after-tax profits of the representative firm in country i are given by:

$$\pi_1^i = f(r_1^i) - (p_1 + \tau_1^i) r_1^i \ , \tag{1}$$

$$\pi_2^i = F(k^i, r_2^i) - (\rho + \kappa^i) k^i - (p_2 + \tau_2^i) r_2^i \ . \tag{2}$$

Profit maximization implies that after-tax returns to both factors are equalized across countries in all periods:

$$f_r(r_1^i) - \tau_1^i = p_1 \ , \tag{3}$$

$$F_r(k^i, r_2^i) - \tau_2^i = p_2 \ , \tag{4}$$

$$F_k(k^i, r_2^i) - \kappa_i = \rho \ . \tag{5}$$

3.2 Resource extraction firms

In each country, there exists a limited, identical and homogenous stock of non-renewable resources, say coal, oil and gas, which can be extracted at zero cost. The resource stock

[2] An alternative interpretation is that the production function is linearly homogenous in capital, resources and a fixed factor such as labor and land like, for example, in Hassler and Krusell (2012). With a fixed factor, deducting capital and resource costs from profits yields the rent accruing to that factor.

[3] Transport costs of resource trade are assumed to be zero.

[4] The capital tax in this model is equivalent to a tax on investment, irrespective of whether investment stems from domestic or foreign sources. In the symmetric equilibrium that I focus on, the capital tax is also equivalent to a tax on savings.

located in country i, Q^i, is managed and fully exploited by a representative resource extraction firm which supplies to a competitive world market q_1^i units of the resource in the present and the remainder, $q_2^i = Q^i - q_1^i$, in the future.[5] Profits of this firm in period t are given by:[6]

$$\Pi_t^i = p_t q_t^i \ . \tag{6}$$

Maximizing the present value of profits subject to the resource constraint and taking world market prices as given, implies that the price of the resource rises with the interest rate:

$$p_2 = p_1(1+\rho) \ . \tag{7}$$

This equation is the well-known Hotelling's rule, which keeps resource extraction firms in all countries indifferent between extracting today and tomorrow (Hotelling, 1931).

Thus, on this competitive resource market, resource demand alone pins down the equilibrium quantities supplied as long as equation (7) holds.[7] How much of the aggregate resource stock $Q = \sum_{l=1}^{n} Q^l$ is extracted in the first period depends on the point of intersection of the aggregate first-period inverse (resource) demand schedule and the aggregate second-period inverse demand schedule, the latter discounted by $1+\rho$. Importantly, this implies that the equilibrium quantity supplied by each of the n resource firms in period one is, in principle, indeterminate. Only *in aggregate* must supply meet demand, $\sum_{l=1}^{n} q_1^l = \sum_{l=1}^{n} r_1^l$, and there is a continuum of supplied quantities that satisfy this equality.

3.3 Households

Each country is populated by a representative household which owns both the production and the resource extraction firm in its country of origin and thus receives the corresponding profits π_t^i and Π_t^i. Any positive revenues from taxing production inputs

[5] None of the results would change if I assumed that the resource owner herself (the representative household to be described next) manages the resource stock.

[6] The focus of this paper is on demand-side policies which is why I neglect any taxes on resource extraction, so-called "severance taxes". Although some U.S. states rely very heavily on severance taxes, most environmental taxes are energy- or transport-related (EEA, 2000). Furthermore, demand-side policies seem to rank higher on the political agenda than supply-side policies.

[7] As shown by Stiglitz (1976), monopoly pricing yields the same result as competitive markets if resource demand elasticities are the same across periods.

are returned lump-sum to consumers in each period:

$$\psi_1^i = \tau_1^i r_1^i \ , \tag{8}$$
$$\psi_2^i = \tau_2^i r_2^i + \kappa^i k^i \ , \tag{9}$$

where ψ_t^i is the sign-unconstrained lump-sum transfer in period t.

First- and second-period consumption, c_1^i and c_2^i, then read:

$$c_1^i = \pi_1^i + \Pi_1^i + \psi_1^i - s^i \ , \tag{10}$$
$$c_2^i = \pi_2^i + \Pi_2^i + \psi_2^i + (1+\rho)s^i \ , \tag{11}$$

where s^i is savings.

The household receives utility from first- and second-period consumption, but is harmed by pollution from global resource use $r_1 = \sum_{l=1}^n r_1^l$ in the first period, $D(r_1)$. One can think of greenhouse gas emissions from burning fossil fuels in production.[8] Welfare of the representative household in country i reads:

$$W^i = U(c_1^i) - D(r_1) + \epsilon c_2^i \ , \tag{12}$$

where $\epsilon \leq 1$ is the discount factor.[9] U is assumed to be concave and twice differentiable while pollution damages are assumed to be weakly convex ($U'' < 0 < U'$, $D' > 0$, $D'' \geq 0$). The quasi-linear specification of the utility function rules out income effects on first-period consumption. This can be justified by empirical evidence that the substitution effect of a marginal change in the interest rate outweighs the income effect (see, for example, Boskin, 1978, or Gylfason, 1993).

Households choose savings s_i to maximize utility (12) subject to budget constraints (10) and (11), taking firm profits, lump-sum transfers and damages as given. From the necessary and sufficient condition for a household maximum (Euler equation),

$$U'(c_1^i) - \epsilon(1+\rho) = 0 \ , \tag{13}$$

[8] I neglect damages in the second period for two reasons. First, the focus of this paper is on how the equilibrium extraction path is influenced by environmental and fiscal policy. Therefore, I am interested in the speed of extraction, which is equivalent to first-period extraction. Second, the natural decay and removal rate of greenhouse gases from the atmosphere is relatively small, and if resources are fully extracted like in this model, the damage in the second period is simply a function of Q and thus a constant.

[9] In contrast to Eichner and Runkel (2012), I do not assume that a physical public good is provided. This would only change the levels of the lump-sum transfer but not any of the tax rates of interest.

we obtain for marginal increases in the interest rate ρ and first-period income π_1^i, Π_1^i or ψ_1^i:

$$\frac{\partial s^i}{\partial \rho} = -\frac{\epsilon}{U''(c_1^i)} > 0 \ , \tag{14}$$

$$\frac{\partial s^i}{\partial \pi_1^i} = \frac{\partial s^i}{\partial \Pi_1^i} = \frac{\partial s^i}{\partial \psi_1^i} = 1 \ . \tag{15}$$

Equation (14) implies a positive capital supply elasticity $(\partial s^i/\partial \rho)\rho/s^i > 0$, and (15) states that, starting from a household optimum, any increase in profits or the lump-sum transfer in the first period increases only second-period consumption via the associated one-to-one increase in savings.

3.4 Global capital market

First-period capital is assumed to be fixed and immobile but second-period capital is perfectly mobile between countries and traded on a global capital market. The equilibrium interest rate ρ on this market is found by equating capital demand by production firms as described by equation (5) and capital supply by households as implicitly characterized by equation (13):

$$\sum_{l=1}^{n} k^l = \sum_{l=1}^{n} s^l \ . \tag{16}$$

In particular, this equation determines ρ as a function of the resource prices p_1 and p_2 and all tax rates τ_1^i, τ_2^i and κ^i in all countries.

3.5 Global resource market

In contrast to the capital market, the resource market needs not only to equate demand and supply across countries but also across periods. One necessary condition for resource markets to clear is Hotelling's rule, equation (7). The other necessary conditions are:

$$\sum_{l=1}^{n} r_1^l = \sum_{l=1}^{n} q_1^l \ , \tag{17}$$

$$\sum_{l=1}^{n} r_2^l = \sum_{l=1}^{n} q_2^l \ . \tag{18}$$

The resource demand functions on the left-hand side are implicitly given by equations (3) and (4), whereas the supply functions on the right-hand-side are indeterminate as long as Hotelling's rule holds. Hotelling's rule and equations (17)–(18) jointly determine the equilibrium world market prices p_1 and p_2 as functions of the interest rate ρ and the tax rates τ_1^i, τ_2^i and κ^i in all countries.

Note that the equilibrium levels of capital and resources used in production are determined by the first-order conditions of profit maximization, (3)–(5), Hotelling's rule (7), equation (13) and the prices implied by the market-clearing conditions (16)–(18), and can thus be expressed as functions of the tax rates τ_1^i, τ_2^i and κ^i in all countries.

4 Comparative statics of unilateral tax policies

Having characterized all demand and supply schedules as well as all market equilibria, we can now calculate the comparative statics of unilateral marginal tax increases. To this end, we totally differentiate equations (3)–(5) for all $i = 1, \ldots, n$ and (7), and insert them into the differentiated conditions (16)–(18), using (14) and (15). The comparative statics with respect to second-period tax rates can be regarded as announcement effects. Starting from a symmetric equilibrium where $k^i = s^i = s$ and $q_t^i = r_t^i$ for all $t = 1, 2$ holds, we arrive at the following results (derived in the Appendix) – first for resource taxes, then for the capital tax.[10]

4.1 Resource taxes

For unilateral marginal increases in the resource taxes τ_1^i (left-hand side of the following equations) and τ_2^i (right-hand side), it holds:

$$\frac{\partial \rho}{\partial \tau_1^i} = -\frac{(1+\rho)(F_{kr} - f_r F_{kk})}{n\Delta} > 0 \;, \qquad \frac{\partial \rho}{\partial \tau_2^i} = \frac{F_{kr} - f_r F_{kk}}{n\Delta} < 0 \;, \tag{19a}$$

$$\frac{\partial p_1}{\partial \tau_1^i} = \frac{p_1 F_{kr} - \Phi - \Theta}{n\Delta} < 0 \;, \qquad \frac{\partial p_1}{\partial \tau_2^i} = \frac{f_{rr}\Omega}{n\Delta} < 0 \;, \tag{19b}$$

[10] As mentioned in Section 3.2, asymmetric extraction across countries is possible and would imply asymmetric resource incomes across countries in the first period. However, I focus on symmetric equilibria where players use the same strategy, i.e., the same tax rates. Identical tax rates, however, can only be a best response if extraction occurs symmetrically such that $q_t^i = r_t^i$ and $s^i = k^i$. Symmetric extraction paths could also be obtained by introducing convex (flow- or stock-dependent) extraction costs that are identical in all countries. Then, the wells with the least cost would be depleted first and equally fast.

$$\frac{\partial p_2}{\partial \tau_1^i} = -\frac{(1+\rho)(\Phi - f_r F_{kr})}{n\Delta} < 0 \ , \qquad \frac{\partial p_2}{\partial \tau_2^i} = \frac{\Phi - f_r F_{kr} - \Delta}{n\Delta} < 0 \ , \tag{19c}$$

where $\Gamma = F_{kk}F_{rr} - (F_{kr})^2 > 0$, $\Phi = F_{rr} - \partial s/\partial\rho\Gamma < 0$, $\Omega = \partial s/\partial\rho F_{kk} - 1 < 0$, $\Theta = f_r(p_1 F_{kk} - F_{kr}) < 0$ and $\Delta = \Phi - p_1 F_{kr} - (1+\rho) f_{rr}\Omega + \Theta < 0$.[11]

Marginal increases in any of the two tax rates lower the world market prices for resources in both periods and also impact on the interest rate. Even under a purely substitutive production technology, $F_{kr} = 0$, the interest rate would be affected since a change in resource use in the first period and the associated change in production go along with a change in savings and thus alter the capital stock in the second period. A second effect on ρ via the capital demand-side arises from the assumed complementarity and goes in the same direction as the capital supply effect: the change in second-period resource use induced by the tax increase changes capital demand through its impact on the marginal product of capital.

For resource use in the tax-increasing country i and all other countries $j \neq i$ and for pollution, we obtain:

$$\frac{\partial r_1^i}{\partial \tau_1^i} = \frac{(n-1)\Delta - (1+\rho) f_{rr}\Omega}{n f_{rr}\Delta} < 0 \ , \qquad \frac{\partial r_1^i}{\partial \tau_2^i} = \frac{\Omega}{n\Delta} > 0 \ , \tag{20a}$$

$$\frac{\partial r_1^j}{\partial \tau_1^i} = \frac{p_1 F_{kr} - \Phi - \Theta}{n f_{rr}\Delta} > 0 \ , \qquad \frac{\partial r_1^j}{\partial \tau_2^i} = \frac{\Omega}{n\Delta} > 0 \ , \tag{20b}$$

$$\frac{\partial r_1}{\partial \tau_1^i} = -\frac{(1+\rho)\Omega}{\Delta} < 0 \ , \qquad \frac{\partial r_1}{\partial \tau_2^i} = \frac{\Omega}{\Delta} > 0 \ , \tag{20c}$$

$$\frac{\partial r_2^i}{\partial \tau_1^i} = \frac{(1+\rho)\Omega}{n\Delta} > 0 \ , \qquad \frac{\partial r_2^i}{\partial \tau_2^i} = \frac{(n-1)F_{kk}\Delta - \Gamma\Omega}{n\Gamma\Delta} < 0 \ , \tag{20d}$$

$$\frac{\partial r_2^j}{\partial \tau_1^i} = \frac{(1+\rho)\Omega}{n\Delta} > 0 \ , \qquad \frac{\partial r_2^j}{\partial \tau_2^i} = -\frac{F_{kk}\Delta + \Gamma\Omega}{n\Gamma\Delta} > 0 \ , \tag{20e}$$

$$\frac{\partial r_2}{\partial \tau_1^i} = \frac{(1+\rho)\Omega}{\Delta} > 0 \ , \qquad \frac{\partial r_2}{\partial \tau_2^i} = -\frac{\Omega}{\Delta} < 0 \ , \tag{20f}$$

where $r_t = \sum_{l=1}^n r_t^l = r_t^i + (n-1) r_t^j$ denotes the total amount of resources used in production in period t.

Unilateral increases in period-t resource taxes have unambiguous and intuitive effects on resource use, as also predicted by partial equilibrium models. A marginal increase in the period-t tax in country i lowers resource use in this country and increases resource

[11] With decreasing returns to scale in production as assumed, Γ is greater than zero. Constant returns to scale would imply $\Gamma = 0$.

use in all other countries in period t via a decline in p_t. We thus have **intratemporal leakage** between countries, which is imperfect in the sense that unilateral efforts to reduce resource use are not completely offset by reactions of market participants in other countries. As in partial equilibrium (where ρ is fixed), a fall in p_t goes along with a fall in the resource price in the other period to facilitate higher resource use in that period and achieve an equilibrium on the resource market. This **intertemporal leakage** effect hits all countries alike. Changes in pollution from aggregate resource use r_1 exhibit the same sign as the effects on first-period resource use in the tax-increasing country. Furthermore, a marginal increase in the second-period tax leads to the effect generally known as the **Green Paradox** (Sinclair, 1992; Sinn, 2008), i.e., an expansion of current resource extraction. This result is in line with van der Meijden et al. (2015) who find that in general equilibrium an attenuation of the Green Paradox (compared to a partial equilibrium treatment) is the most likely outcome if the second-period tax rate is increased and investment in physical capital is possible. In fact, unless the income effect outweighs the substitution effect (which is unlikely as argued above), a reversal of the Green Paradox, i.e., a reduction of current extraction induced by an increase in future resource taxes, cannot happen in their model.

Denoting the total stock of capital in the second period by $k = \sum_{l=1}^{n} k^l = k^i + (n-1)k^j$, we further derive:

$$\frac{\partial k^i}{\partial \tau_1^i} = \frac{(1+\rho)\left[f_r - \frac{\partial s}{\partial \rho} F_{kr}\right]}{n\Delta} \gtreqless 0 \ , \qquad \frac{\partial k^i}{\partial \tau_2^i} = \frac{F_{kr}\left[\frac{\partial s}{\partial \rho}\Gamma - (n-1)\Delta\right] - f_r\Gamma}{n\Gamma\Delta} \gtreqless 0 \ , \tag{21a}$$

$$\frac{\partial k^j}{\partial \tau_1^i} = \frac{(1+\rho)\left[f_r - \frac{\partial s}{\partial \rho} F_{kr}\right]}{n\Delta} \gtreqless 0 \ , \qquad \frac{\partial k^j}{\partial \tau_2^i} = \frac{F_{kr}\left[\frac{\partial s}{\partial \rho}\Gamma + \Delta\right] - f_r\Gamma}{n\Gamma\Delta} > 0 \ , \tag{21b}$$

$$\frac{\partial k}{\partial \tau_1^i} = \frac{(1+\rho)\left[f_r - \frac{\partial s}{\partial \rho} F_{kr}\right]}{\Delta} \gtreqless 0 \ , \qquad \frac{\partial k}{\partial \tau_2^i} = \frac{\frac{\partial s}{\partial \rho} F_{kr} - f_r}{\Delta} \gtreqless 0 \ . \tag{21c}$$

For a purely substitutive relationship between capital and resources in production, $F_{kr} = 0$, the change in capital use would solely be driven by the change in savings due to the intertemporal reallocation of resource use. We have seen that a marginal change in τ_t^i lowers domestic and aggregate resource use in period t but increases resource use in the other period. If, e.g., it *increased* first-period resource use, more output would be produced and the associated increase in profits would translate one-to-one into higher savings and thus higher capital investment in the second period. With complementarity, capital use is also affected by the change in resource use following marginal tax changes. To stick with our example, declining second-period resource use would go along with decreasing capital demand (at home and in aggregate) and an interest rate that is decreasing by more than under perfect substitutability, implying lower savings. This effect thus counteracts the first (direct) effect implying increased savings, and it is unclear which effect is stronger. Only for a marginal increase in τ_2^i does investment in all countries $j \neq i$ unambiguously rise.

4.2 Capital tax

A marginal increase in the capital tax κ^i has the following effects on world market prices:

$$\frac{\partial \rho}{\partial \kappa^i} = -\frac{(1+\rho) f_{rr} + F_{rr} - f_r F_{kr}}{n\Delta} < 0 \ , \tag{22a}$$

$$\frac{\partial p_1}{\partial \kappa^i} = \frac{f_{rr}\left[p_1 - \frac{\partial s}{\partial \rho} F_{kr}\right]}{n\Delta} \gtreqless 0 \ , \tag{22b}$$

$$\frac{\partial p_2}{\partial \kappa^i} = -\frac{p_1 (F_{rr} - f_r F_{kr}) + (1+\rho) f_{rr} \frac{\partial s}{\partial \rho} F_{kr}}{n\Delta} < 0 \ . \tag{22c}$$

As intuition suggests, a marginal increase in κ^i depresses the interest rate. The second-period price for the resource falls while the effect on the first-period resource price is ambiguous in sign, depending on the term $p_1 - \partial s / \partial \rho F_{kr}$.

Concerning changes in investment in the tax-increasing country i and all other countries $j \neq i$, we find:

$$\frac{\partial k^i}{\partial \kappa^i} = \frac{(n-1) F_{rr} \Delta - \frac{\partial s}{\partial \rho} \Gamma [(1+\rho) f_{rr} + F_{rr}] + p_1 f_r \Gamma}{n \Gamma \Delta} < 0 \ , \tag{23a}$$

$$\frac{\partial k^j}{\partial \kappa^i} = \frac{F_{kr}[p_1 F_{rr} + (1+\rho) f_{rr} \frac{\partial s}{\partial \rho} F_{kr}] - F_{rr}[(1+\rho) f_{rr} + F_{rr}] + p_1 f_r \Gamma}{n \Gamma \Delta} > 0 \ , \tag{23b}$$

$$\frac{\partial k}{\partial \kappa^i} = \frac{p_1 f_r - \frac{\partial s}{\partial \rho}[(1+\rho) f_{rr} + F_{rr}]}{\Delta} < 0 \ . \tag{23c}$$

A marginal increase in κ^i lowers investment in the tax-increasing country but increases investment in all other countries due to the declining interest rate and the declining resource price p_2. Aggregate investment falls.

Furthermore, we have:

$$\frac{\partial r_1^i}{\partial \kappa^i} = \frac{p_1 - \frac{\partial s}{\partial \rho} F_{kr}}{n\Delta} \gtreqless 0 \ , \tag{24a}$$

$$\frac{\partial r_1^j}{\partial \kappa^i} = \frac{p_1 - \frac{\partial s}{\partial \rho} F_{kr}}{n\Delta} \gtreqless 0 \ , \tag{24b}$$

$$\frac{\partial r_1}{\partial \kappa^i} = \frac{p_1 - \frac{\partial s}{\partial \rho} F_{kr}}{\Delta} \gtreqless 0 \ , \tag{24c}$$

$$\frac{\partial r_2^i}{\partial \kappa^i} = -\frac{(n-1)F_{kr}\Delta + \Gamma \left[p_1 - \frac{\partial s}{\partial \rho} F_{kr}\right]}{n\Gamma\Delta} \gtreqless 0 \ , \tag{24d}$$

$$\frac{\partial r_2^j}{\partial \kappa^i} = \frac{F_{kr}\Delta - \Gamma \left[p_1 - \frac{\partial s}{\partial \rho} F_{kr}\right]}{n\Gamma\Delta} > 0 \ , \tag{24e}$$

$$\frac{\partial r_2}{\partial \kappa^i} = -\frac{p_1 - \frac{\partial s}{\partial \rho} F_{kr}}{\Delta} \gtreqless 0 \ . \tag{24f}$$

The signs of most of the equations above depend on the sign of the term $p_1 - \partial s/\partial\rho F_{kr}$. Assume for the moment a purely substitutive technology, i.e., $F_{kr} = 0$. Then, all effects have a unique sign: as capital becomes more expensive for the production firm in country i due to the marginal tax increase, it will substitute away from capital into more resource use. The accompanying fall in the second-period resource price and the decrease in the interest rate stimulate resource use in all other countries in that period. A symmetric decline in first-period resource use (and pollution) results, going along with an increase in p_1. A unilateral increase in capital taxes thus *slows down* resource extraction whenever capital and resources are perfect substitutes.

For $F_{kr} > 0$, the sign of $p_1 - \partial s/\partial\rho F_{kr}$ is determined by the complex interplay in general equilibrium and difficult to qualify analytically since the degree of complementarity between capital and resources as measured by F_{kr} also plays a role in pinning down p_1. A sufficiently high degree of complementarity, i.e., a sufficiently high value of F_{kr}, causes the whole term to be negative, leading to lower second-period resource use in the tax-increasing country. The intuition is that a unilateral increase in the capital tax also puts a burden on the resource input whenever complementarity is sufficiently high. Although resource demand in all other countries is spurred by a decline in p_2 and ρ, the direct effect outweighs the indirect effects in all other countries such that global resource use in the future falls. A unilateral increase of the capital tax then *speeds up* global resource extraction and increases pollution, accompanied by a decrease in p_1.

Similar effects can be observed for a sufficiently high capital supply elasticity as measured by $\partial s/\partial \rho$ (and for F_{kr} strictly positive). A higher $\partial s/\partial \rho$ implies that savings respond more sharply to the decrease in ρ associated with the increase in κ^i. With less capital supply and investment in the second period, also aggregate resource use in the second period decreases, and aggregate first-period resource use goes up.

Summing up the comparative statics results, we can establish the following proposition.

Proposition 1 (Effects of unilateral tax policies)
Unilateral marginal increases in

- *future capital taxes may speed up or slow down first-period extraction, depending on the degree of complementarity between capital and resources in production and the size of the capital supply elasticity;*
- *period-t resource taxes shift resource use towards other countries but depress aggregate resource use in period t (less than 100% intratemporal leakage) and thus increase global resource use in the other period. This implies Green Paradox effects.*

5 Pareto-optimal policies and strategic interactions

In this section, I first derive the benchmark case of Pareto-optimal policies and then assess the efficiency properties of the Nash equilibrium under different scenarios.

5.1 Pareto-optimal policies

Pareto-optimal policies are found by maximizing lifetime utility W^i, equation (12), s.t. $W^j = \overline{W}^j$, $\forall j \neq i$, by choosing κ^i, τ_1^i and τ_2^i. Further constraints are the budget constraints of each household, given by (10) and (11), where firm profits and lump-sum transfers (both of which are exogenous from the perspective of households) are replaced by (1) and (2) respectively (8) and (9). Furthermore, the conditions of utility maximization, (13)–(15), profit maximization, (3)–(7), and the market reactions as described by (19a)–(24f) need to be considered. Focusing on the symmetric solution with $s^i = k^i = s$

and $q_t^i = r_t^i$, the first-order conditions for the tax rates in country i read:[12]

$$(1+\rho)\tau_1^i \frac{\partial r_1}{\partial \tau_1^i} + \tau_2^i \frac{\partial r_2}{\partial \tau_1^i} + \kappa^i \frac{\partial k}{\partial \tau_1^i} - \frac{nD'(r_1)}{\epsilon}\frac{\partial r_1}{\partial \tau_1^i} = 0 \ , \tag{25}$$

$$(1+\rho)\tau_1^i \frac{\partial r_1}{\partial \tau_2^i} + \tau_2^i \frac{\partial r_2}{\partial \tau_2^i} + \kappa^i \frac{\partial k}{\partial \tau_2^i} - \frac{nD'(r_1)}{\epsilon}\frac{\partial r_1}{\partial \tau_2^i} = 0 \ , \tag{26}$$

$$(1+\rho)\tau_1^i \frac{\partial r_1}{\partial \kappa^i} + \tau_2^i \frac{\partial r_2}{\partial \kappa^i} + \kappa^i \frac{\partial k}{\partial \kappa^i} - \frac{nD'(r_1)}{\epsilon}\frac{\partial r_1}{\partial \kappa^i} = 0 \ . \tag{27}$$

Rearranging these conditions and denoting $\kappa^i = \kappa^*$, $\tau_1^i = \tau_1^*$ and $\tau_2^i = \tau_2^*$ yields the following Pareto-optimal tax rates:

$$\kappa^* = 0 \ , \tag{28}$$

$$\tau_1^* - \frac{\tau_2^*}{1+\rho} = \frac{nD'(r_1)}{U'(c_1^i)} = \frac{nD'(r_1)}{\epsilon(1+\rho)} \ . \tag{29}$$

The Pareto-optimal capital tax rate κ^* equals zero. The social marginal environmental damage, $nD'(r_1)$, from aggregate resource use in the first period, expressed in units of the first-period consumption good, is fully internalized through the use of resource taxes. There is one degree of freedom in setting Pareto-optimal resource taxes τ_1^* and τ_2^*. Either one of the two tax rates is set to zero and a positive first-period/negative second-period resource tax is implemented, or a convex combination of both instruments that satisfies equation (29) is used. In any case, the tax profile is falling over time, with a weakly positive tax in the first and a weakly negative tax in the second period.[13] The intuition is that it is not the static value of the tax rate in one period that matters for the internalization of the external effect but rather its development over time. Only a falling tax schedule incentivizes firms to postpone extraction relative to a laissez-faire scenario without taxes.

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[12] The resource quantities supplied by each country are, in principle, indeterminate as argued in Section 3.2 and footnote 10 (only in symmetric equilibrium, we have $q_t^i = r_t^i$ and thus $s^i = k^i$ for all i). This also implies that the derivatives of the supplied quantities with respect to the tax rates $\square = \kappa^i, \tau_1^i, \tau_2^i$ are zero for any time period t: $\partial q_t^i / \partial \square = 0$. With symmetric extraction costs, we would have: $\partial q_t^i / \partial \square = (1/n) \partial r_t / \partial \square$, implying that any tax-induced change in aggregate resource demand is met by equal changes in supply by all resource firms. Both approaches lead to the same first-order conditions in the Pareto-optimum as well as in the decentralized equilibria inspected below.

[13] Pareto-optimal resource tax rates that decline over time have also been found by, e.g., Sinclair (1992, 1994) and Golosov et al. (2014).

5.2 Dezentralized equilibrium

I now proceed to characterize the equilibrium of the Nash game, assuming that governments can fully commit to the vector of tax rates, which implies that they do not deviate from their announced policies in the second period. Obviously, this is not an innocuous assumption and will be addressed in the Discussion section.

In each country, the benevolent government non-cooperatively maximizes its resident's lifetime utility by choosing κ^i, τ_1^i and τ_2^i, taking the policies of all other countries as given. In doing so, it takes the household's budget constraint into account, equations (10) and (11), and replaces in these equations firm profits by (1) and (2) and lump-sum transfers by (8) and (9). It also considers the conditions of utility maximization, (13)–(15), profit maximization, (3)–(7), and the market reactions (19a)–(19c), (20a), (20d), (21a), (22a)–(22c), (23a), (24a) and (24d). Assuming that a symmetric equilibrium with an interior solution exists, it is described by the following first-order conditions:

$$(1+\rho)\tau_1^i \frac{\partial r_1^i}{\partial \tau_1^i} + \tau_2^i \frac{\partial r_2^i}{\partial \tau_1^i} + \kappa^i \frac{\partial k^i}{\partial \tau_1^i} - \frac{D'(r_1)}{\epsilon} \frac{\partial r_1}{\partial \tau_1^i} = 0 \ , \tag{30}$$

$$(1+\rho)\tau_1^i \frac{\partial r_1^i}{\partial \tau_2^i} + \tau_2^i \frac{\partial r_2^i}{\partial \tau_2^i} + \kappa^i \frac{\partial k^i}{\partial \tau_2^i} - \frac{D'(r_1)}{\epsilon} \frac{\partial r_1}{\partial \tau_2^i} = 0 \ , \tag{31}$$

$$(1+\rho)\tau_1^i \frac{\partial r_1^i}{\partial \kappa^i} + \tau_2^i \frac{\partial r_2^i}{\partial \kappa^i} + \kappa^i \frac{\partial k^i}{\partial \kappa^i} - \frac{D'(r_1)}{\epsilon} \frac{\partial r_1}{\partial \kappa^i} = 0 \ . \tag{32}$$

Each government trades off the marginal benefits with the marginal costs of tax changes. These changes affect tax revenues by altering the domestic tax bases in both periods (first three terms in the above equations), and environmental damage by altering aggregate resource use in the first period (last term above). Compared to equations (25)–(27), we observe that governments do not take into account aggregate pollution damages and the effects of their policies on aggregate variables.

To gain an understanding of the governments' strategic behavior, I will first discuss the Nash equilibrium with resource taxes only, then the equilibrium with a capital tax only, and finally describe the equilibrium with all instruments available.

5.2.1 Nash equilibrium with resource taxes only

Because of their partial equilibrium nature, most models in the literature allow governments to only have resource taxes at their disposal. In this case, equation (32) drops out, and the optimal tax rates in the symmetric Nash equilibrium in country i can be obtained by rearranging conditions (30) and (31) for $\kappa^i = 0$:

$$\tau_1^i = -\frac{nD'(r_1)}{\epsilon} \frac{f_{rr}F_{kk}\Omega}{(n-1)F_{kk}\Delta - \Omega\left[\Gamma + (1+\rho)f_{rr}F_{kk}\right]} > 0 \ , \tag{33}$$

$$\tau_2^i = \frac{nD'(r_1)}{\epsilon} \frac{\Gamma\Omega}{(n-1)F_{kk}\Delta - \Omega\left[\Gamma + (1+\rho)f_{rr}F_{kk}\right]} < 0 \ . \tag{34}$$

The marginal benefits of a marginal increase in τ_1^i or decrease in τ_2^i are that they lower domestic and aggregate resource use in the first period, thereby reducing environmental damage and increasing resource tax revenue in the second period, see equations (30)–(31). The associated marginal cost is the loss of resource tax revenue in the first period. While the resource taxes' time profile in the Nash equilibrium is falling like in the efficient solution, the degree of freedom in setting this tax-subsidy combination vanishes. Now a strictly positive tax in the first and a strictly negative tax rate in the second period prevail.

To assess the efficiency properties of the Nash equilibrium, we cannot simply compare the Pareto-optimal tax-subsidy combination with the tax-subsidy combination in the Nash equilibrium because world market prices and the derivatives contained in the tax rate equations are endogenous. Instead, we examine the policy externalities, i.e., the effects of marginal tax increases in country i on welfare in country $j \neq i$, starting from the symmetric Nash equilibrium. For $\square = \tau_1, \tau_2$, we obtain the following externalities:

$$\frac{\partial W^j}{\partial \square^i} = -D'(r_1)\frac{\partial r_1}{\partial \square^i} + \epsilon(1+\rho)\tau_1^j \frac{\partial r_1^j}{\partial \square^i} + \epsilon\tau_2^j \frac{\partial r_2^j}{\partial \square^i} \ . \tag{35}$$

Inserting the Nash equilibrium tax rates and the comparative statics results into (35), it can be shown that a marginal increase in τ_1^i (or a marginal decrease in τ_2^i) exerts a positive environmental externality on country j (first term in above equation). Additionally, two private income externalities (second and third term) arise that change the tax bases in country j due to resource mobility.[14] They have different signs but are strictly positive in aggregate.

Furthermore, we can establish the following lemma.

[14] As tax revenues are recycled lump-sum to consumers, I refer to these externalities as 'private income' externalities as in Eichner and Runkel (2012). Introducing a physical public good into this model would not change any of the results derived here except that the 'private income' externalities could then be called 'fiscal'.

Lemma 1 (Policy externalities of τ_1^i and τ_2^i)
A marginal increase in τ_1^i has the opposite effect in present value terms of a marginal increase in τ_2^i:

$$\frac{\partial W^j}{\partial \tau_2^i} = -\frac{1}{1+\rho}\frac{\partial W^j}{\partial \tau_1^i} = -\frac{nD'(r_1)F_{kk}\Omega}{(n-1)F_{kk}\Delta - \Omega[\Gamma + (1+\rho)f_{rr}F_{kk}]} < 0 \ . \tag{36}$$

Both policy externalities are thus related to the environmental damage in country j.

With only one instrument, a positive (negative) externality would imply that the tax rate in the Nash equilibrium is set inefficiently low (high). However, we have two instruments and therefore need to make use of the following lemma (the proof of which can be found in the Appendix) to be able to say something about whether the Nash equilibrium tax-subsidy combination $\tau_1^i - \tau_2^i/(1+\rho)$ is inefficiently high or low.

Lemma 2 (Aggregate resource use and pollution)
For given tax policies in all other countries, aggregate resource use and pollution are determined by the difference $\tau_1^i - \tau_2^i/(1+\rho)$.

A marginal increase in the tax-subsidy combination $\tau_1^i - \tau_2^i/(1+\rho)$ which can be brought about by either increasing τ_1^i or decreasing τ_2^i (or both) thus exerts a positive externality on all other countries $j \neq i$ such that we can state the following proposition.

Proposition 2 (Inefficiently high pollution in (τ_1^i, τ_2^i)-Nash equilibrium)
The tax-subsidy combination in the Nash equilibrium with environmental taxes only is set inefficiently low and thus aggregate first-period resource use in the first period (equal to pollution) is inefficiently high.

Like in Eichner and Runkel (2012) for the case of perfect pollution spillovers ($\beta = 1$ in their model), environmental and private income externalities go in the same direction and imply inefficiently low equilibrium tax rates and thus inefficiently high resource use in the first period.[15]

[15] This is indeed the standard result in the environmental tax competition literature. Only Oates and Schwab (1988) and Ogawa and Wildasin (2009) find efficiency of decentralized policy-making, while a race to the top in environmental regulation has been shown when pollution affects the marginal productivity of capital (Rauscher, 1997) or when households anticipate government policies (Withagen and Halsema, 2013).

5.2.2 Nash equilibrium with capital tax only

In the unlikely case that governments are restricted – for whatever reason – to using capital taxes, conditions (30) and (31) drop out. For $\tau_1^i = \tau_2^i = 0$, the first-order condition (32) for country i in the symmetric Nash equilibrium can be written as:

$$\kappa^i = \frac{nD'(r_1)}{\epsilon} \frac{\left[p_1 - \frac{\partial s}{\partial \rho} F_{kr}\right] \Gamma}{(n-1)F_{rr}\Delta - \frac{\partial s}{\partial \rho}\Gamma\left[(1+\rho)f_{rr} + F_{rr}\right] + p_1 f_r \Gamma} \ . \tag{37}$$

Specifically, a marginal capital tax increase reduces tax revenue due to the associated capital outflow but may increase or decrease aggregate first-period resource use and thus pollution. The sign of the capital tax is thus ambiguous and solely depends on the term $p_1 - \partial s/\partial \rho F_{kr}$ in the numerator:

$$\kappa^i \gtreqless 0 \Leftrightarrow p_1 - \frac{\partial s}{\partial \rho} F_{kr} \gtreqless 0 \ . \tag{38}$$

It is – like nearly all ambiguous comparative statics results in Section 4.2 – driven by the complex interplay of p_1, $\partial s/\partial \rho$ and F_{kr}. In particular, the capital tax is negative whenever the degree of complementarity between capital and resources is sufficiently high. In this case, a negative capital tax implicitly subsidizes second-period resource use, which is desired in order to lower resource use and thus pollution in the first period. The more substitutive the production technology is, the more likely is it that governments discourage first-period resource use by taxing capital use in the second period. Since the externality-generating input cannot directly be targeted by the government in this scenario, we can suspect (and it will be shown in the numerical illustrations of Section 5.3) that not only inefficiently high first-period extraction will prevail but that extraction is also higher than in the Nash equilibrium with resource taxes only.[16]

5.2.3 Nash equilibrium with resource and capital taxes

If each government is equipped with the full set of tax instruments, additional considerations enter the governments' trade-off between marginal costs and marginal benefits. In particular, marginal changes in resource taxes now affect capital tax revenue. These effects are ambiguous in sign since investment in country i may rise or fall due to a marginal increase in τ_1^i or τ_2^i, see equation (21c). Similarly, a marginal capital tax increase may

[16] Calculating the policy externality does not yield much insight here because we would have to contrast it with a constrained Pareto-optimum in which the capital tax is the only available instrument.

positively or negatively affect resource tax revenues. The first-order conditions (30)–(32) can be rearranged to yield:

$$\tau_1^i = -\frac{D'(r_1)}{\epsilon} \frac{f_{rr}\left[(n-1) - n\frac{\partial s}{\partial \rho}F_{kk}\right]}{\frac{\partial s}{\partial \rho}\left[\Gamma + (1+\rho)f_{rr}F_{kk}\right] - (n-1)\Delta} > 0 \ , \tag{39}$$

$$\tau_2^i = \frac{D'(r_1)}{\epsilon} \frac{(n-1)(F_{rr} - p_1 F_{kr}) - n\frac{\partial s}{\partial \rho}\Gamma}{\frac{\partial s}{\partial \rho}\left[\Gamma + (1+\rho)f_{rr}F_{kk}\right] - (n-1)\Delta} < 0 \ , \tag{40}$$

$$\kappa^i = \frac{D'(r_1)}{\epsilon} \frac{(n-1)(F_{kr} - p_1 F_{kk})}{\frac{\partial s}{\partial \rho}\left[\Gamma + (1+\rho)f_{rr}F_{kk}\right] - (n-1)\Delta} > 0 \ . \tag{41}$$

As before, resource taxes decline over time, with a strictly positive tax in the first and a strictly negative tax in the second period. Interestingly, the capital tax is strictly positive. This is surprising since most comparative statics results of marginal capital tax increases are ambiguous in sign, and we have seen that the sign of the equilibrium capital tax is also ambiguous whenever resource taxes are not available. By looking at the terms in the numerator of equation (41), we can shed light on the effects at work. By increasing the capital tax from zero to a positive value, a government is able to induce the firms in all other $n-1$ countries to use more resources in the second and less resources in the first period, thereby slowing down aggregate resource extraction. This occurs through a channel which I will refer to as the *capital-tax-interest-rate channel*. The latter unfolds its effects through the decrease in the interest rate associated with an increase in the capital tax (see also equation (22a) for a marginal tax increase): First, the falling interest rate makes investment in non-tax-increasing countries more attractive and thus spurs, due to complementarity of capital and resources, resource demand abroad (first term in the numerator of (41)). Second, there is a Hotelling rule effect (second term in the numerator) which applies even for a purely substitutive production technology. That is, the fall in the interest rate is accompanied by a fall in p_2 which again induces production firms abroad to demand more resources in the second period. Because of these two effects, each government finds it beneficial to employ a strictly positive capital tax in equilibrium. More intuition on the capital-tax-interest-rate channel will be provided in the next section.

With three instruments at the governments' disposal, it is impossible to show analytically whether aggregate first-period resource extraction is inefficiently high or low in the Nash equilibrium. Therefore, I have to rely on numerical illustrations. However, there is no reason which would speak for inefficiently low first-period resource extraction if we allow for an additional instrument (the capital tax).

5.3 Numerical illustration

So far, we have seen that the Nash equilibrium when only resource taxes are available entails inefficiently high resource extraction in the present, and we have suspected the same thing also for the other two scenarios. In order to show the impact of environmental and private income externalities on the efficiency of decentralized policy-making and quantify the effects at work, some numerical illustrations are provided below. I am particularly interested in by how much an additional capital tax lowers first-period resource extraction and which role the elasticity of substitution between capital and resources plays in this regard.

To have an additional benchmark, I sketch the Nash equilibrium under autarky, i.e., when factors of production are immobile. In this case, there are n purely national capital and resource markets. I denote the prices on these markets by ρ^i, p_1^i and p_2^i in country i. The modified comparative statics of unilateral marginal tax increases can easily be derived by setting $n = 1$ in equations (19a)–(24f). Note that there is no leakage anymore since capital and resources are not traded across borders. With these modified comparative statics results, government maximization yields the following tax rates κ^{i0}, τ_1^{i0} and τ_2^{i0} in the autarky Nash equilibrium in each country:

$$\kappa^{i0} = 0 \ , \tag{42}$$

$$\tau_1^{i0} - \frac{\tau_2^{i0}}{1+\rho^i} = \frac{D'(r_1)}{\epsilon(1+\rho^i)} \ . \tag{43}$$

The government internalizes the environmental externality imposed on own utility by choosing a convex combination of resource taxes. This is in fact the standard textbook case where environmental spillovers are the only externality imposed on other countries.[17] As the capital and resource allocation in other countries cannot be influenced via tax policies, environmental taxes target the externality best, and there is no role for capital taxation in this world of closed economies.

For the numerical simulations, I choose a logarithmic first-period utility function and a quadratic damage function such that equation (12) now reads:

$$W^i = ln(c_1^i) - \frac{1}{2}(r_1)^2 + \epsilon c_2^i \ . \tag{44}$$

[17] To see this analytically, cf. equation (35) where the fiscal externalities are zero under autarky since it holds for all $t = 1, 2$ and all $j \neq i$: $\partial r_t^j / \partial \tau_1^i = \partial r_t^j / \partial \tau_2^i = 0$.

For production, I use a standard CES function:

$$F(k_t^i, r_t^i) = \left[(k_t^i)^\alpha + (r_t^i)^\alpha\right]^{\frac{z}{\alpha}} \ , \tag{45}$$

where z describes the degree of homogeneity and $z < 1$ is assumed because of decreasing returns to scale. The elasticity of substitution σ equals $1/(1-\alpha)$, i.e., the lower is α, the more complementary are capital and resources. Note that for F_{kr} to be positive, $z > \alpha$ has to hold.[18]

The following two tables illustrate the results obtained under different scenarios for $n = 2$ and $Q^i \equiv 1$. The laissez-faire scenario involves no government intervention (all tax rates equal zero), which obviously is not an equilibrium. NE stands for a Nash equilibrium either without factor mobility ("w/o mobility"), with only κ^i, only τ_1^i and τ_2^i, or all instruments at the governments' disposal. $p_1^{(i)}$ and $\rho^{(i)}$ denote the equilibrium prices on the national (with superscript $^{(i)}$) respectively international (without superscript) factor markets. The displayed parameter constellations are just exemplary but the derived results hold qualitatively for all other constellations that I examined such that they are representative in a *pars pro toto* sense.[19]

The ranking of scenarios *with respect to first-period resource use* remains the same across all parameter constellations. Laissez-faire and Pareto-optimum describe the two extreme cases, and the autarky NE always entails lower first-period resource extraction than all NE with factor mobility since the environmental externality is not aggravated by factor mobility in this scenario. Furthermore, the NE with three instruments gives rise to lower first-period resource use than the resource-taxes-only scenario which, in turn, outperforms the capital-tax-only NE. We can summarize these results in the following proposition.

Proposition 3 (Inefficiently high resource extraction in all Nash equilibria) *All Nash equilibria involve inefficiently high first-period resource extraction and thus pollution. Factor mobility unambiguously increases resource extraction.*

In this regard, the paper generalizes the results obtained by Eichner and Runkel (2012) who find an inefficiently low tax rate on capital (and thus emissions) in their framework, implying inefficiently high pollution. While Eichner and Runkel's analysis is limited to the case of perfect complementarity between capital and emissions, this paper explicitly

[18] Strict quasi-concavity requires $\alpha < 1$ (Uzawa, 1962), which holds as I assume decreasing returns to scale and a positive cross-partial derivative F_{kr}, i.e., $\alpha < z < 1$.
[19] There might be parameter constellations for which an equilibrium does not exist though.

	r_1^i ($p_1^{(i)}$)	k^i ($\rho^{(i)}$)	τ_1^i	τ_2^i	κ^i	W^i
	$\alpha = -5$ $(\sigma = 1/6)$					
Laissez-faire	.89 (.46)	.11 (.49)	–	–	–	-1.63
Pareto-optimum	.47 (.88)	.09 (1.36)	–	-4.17	–	-.96
NE w/o mobility	.66 (.72)	.19 (1.08)	–	-2.95	–	-1.08
NE κ^i	.86 (.50)	.17 (.64)	–	–	-.70	-1.53
NE τ_1^i, τ_2^i	.72 (.17)	.19 (.97)	1.00	-.48	–	-1.17
NE $\kappa^i, \tau_1^i, \tau_2^i$	.68 (.09)	.16 (.95)	1.24	-.33	.39	-1.11
	$\alpha = 0.5$ $(\sigma = 2)$					
Laissez-faire	.75 (1.18)	1.91 (.74)	–	–	–	2.47
Pareto-optimum	.37 (1.57)	1.44 (.88)	–	-3.25	–	3.04
NE w/o mobility	.489 (1.40)	1.61 (.83)	–	-2.17	–	2.983
NE κ^i	.74 (1.19)	1.87 (.68)	–	–	.15	2.51
NE τ_1^i, τ_2^i	.51 (1.03)	1.63 (.83)	.71	-.73	–	2.96
NE $\kappa^i, \tau_1^i, \tau_2^i$	.491 (1.06)	1.58 (.75)	.66	-.77	.18	2.980

Table 1: Simulation results for $z = 0.75$, $\bar{k} = 1$ and $\epsilon = 0.9$.

	$\alpha = 0.3$ ($\sigma = 10/7$)					
	r_1^i ($p_1^{(i)}$)	k^i ($\rho^{(i)}$)	τ_1^i	τ_2^i	κ^i	W^i
Laissez-faire	.632 (2.60)	2.36 (2.42)	–	–	–	7.670
Pareto-optimum	.52 (2.75)	2.09 (2.68)	–	-5.21	–	7.809
NE w/o mobility	.572 (2.68)	2.22 (2.56)	–	-2.86	–	7.780
NE κ^i	.630 (2.60)	2.35 (2.41)	–	–	-.05	7.676
NE τ_1^i, τ_2^i	.60 (2.51)	2.29 (2.49)	.25	-.51	–	7.732
NE $\kappa^i, \tau_1^i, \tau_2^i$	.574 (2.59)	2.21 (2.42)	.175	-1.51	.28	7.777
	$\alpha = 0.7$ ($\sigma = 10/3$)					
Laissez-faire	.940 (1.02)	.61 (1.04)	–	–	–	-1.14
Pareto-optimum	.38 (1.12)	.15 (1.66)	–	-3.79	–	-.13
NE w/o mobility	.55 (1.08)	.28 (1.38)	–	-2.73	–	-.23
NE κ^i	.937 (1.02)	.59 (1.01)	–	–	.07	-1.13
NE τ_1^i, τ_2^i	.73 (.88)	.43 (1.20)	.32	-1.12	–	-.53
NE $\kappa^i, \tau_1^i, \tau_2^i$	.61 (.91)	.16 (.74)	.31	-.84	1.57	-.37

Table 2: Simulation results for $z = 0.95$, $\bar{k} = 0.1$ and $\epsilon = 0.8$.

takes account of the fact that emissions are not simply a by-product of investment but caused by the burning of fossil resources in production and can be substituted for capital to some degree.

Table 1 illustrates that the capital-tax-only policy does, unsurprisingly, not internalize much of the environmental externality, the reason being that it does not target the externality-generating input directly and thus only serves as an imperfect policy substitute for environmental taxes. Furthermore, our above intuition is confirmed that a higher degree of complementarity between capital and resources ($\alpha = 0.5$) does indeed make a capital subsidy more likely.

The ranking of scenarios *with respect to welfare* is – as expected – the inverse of the ranking with respect to first-period extraction. Interestingly, although we might suspect that the introduction of a capital tax adds to the distortions already present in the economy, welfare in the NE with all instruments available is unambiguously higher than in the resource-taxes-only NE. The reason is that the capital tax makes an additional instrument available to governments, which is – through the capital-tax-interest-rate channel – able to improve the resource (and capital) allocation across space and across time. As a result, countries are better off if they use the capital tax as an additional instrument:

Proposition 4 (($\kappa^i, \tau_1^i, \tau_2^i$)-NE Pareto-dominates ($\tau_1^i, \tau_2^i$)-NE)
The use of a capital tax in addition to resource taxes Pareto-dominates the scenario with resource taxes only.

Furthermore, the private income externalities due to factor mobility are not necessarily very large. In particular, a higher degree of complementarity between capital and resources seems to bring about smaller private income externalities such that first-period resource extraction nearly coincides in the autarky NE, the NE with environmental taxes only and the NE with all instruments available.

Finally, as can be seen in both tables, the capital tax in the NE with all instruments is relatively small when the elasticity of substitution is low while for a higher degree of substitutability, the capital tax is higher and achieves a more significant reduction of first-period resource use relative to the NE with environmental taxes only. The reason is that in the latter case, the capital tax significantly lowers the interest rate and thus spurs second-period resource use through the capital-tax-interest-rate channel described above. This channel is the stronger, the higher is the elasticity of substitution. The following proposition summarizes these results.

Proposition 5 (Elasticity of substitution and decentralized policy-making) *Whenever the elasticity of substitution between capital and resources is low, factor mobility does not significantly worsen efficiency compared to the autarky Nash equilibrium. A high elasticity of substitution, by contrast, strengthens the capital-tax-interest-rate channel and thus makes the introduction of an additional strictly positive capital tax more attractive in terms of lowering aggregate first-period resource use.*

6 Discussion

As a remedy to Green Paradox effects like in this model, Sinn (2008) proposes a so-called supply-side policy, namely a source-based tax on capital income earned by foreign resource owners in industrialized countries. He argues that this tax will (in partial equilibrium) depress the net interest rate on reproducible capital and thus make extraction less attractive to resource owners.[20] This paper, by contrast, suggests that not necessarily a supply-side policy needs to be adopted to bring the interest rate down and thus decelerate resource extraction. As we have seen, also a demand-side policy, specifically the source-based taxation of capital investment on the side of production firms is able to tilt the extraction path in the right direction – even in a world where countries compete for mobile factors of production. This policy might in fact be more realistic because policy-makers still seem to pay more attention to demand-side policies. In contrast to Sinn's proposal, the capital tax does not replace resource taxes. In fact, as illustrated in the last section, using a capital tax *in addition* to resource taxes Pareto-dominates the solitary use of resource taxes.

A natural question that arises in this two-period model is how a third period would influence the results. As it seems impossible to answer this question analytically (we would have to introduce two additional markets, the capital and the resource market in the third period, which would complicate the analysis enormously), some plausible reasoning shall be attempted here. With a third period, we would have to model damages also in the second period in order to give governments an incentive to shift resource extraction through their tax policies from the second to the third period.[21] I conjecture

[20] Jaakkola (2012) confirms in a two-country Ramsey growth model that a tax on the resource-exporting country's capital income is indeed able to achieve an efficient solution when this country does not produce goods.

[21] Possibly, the natural decay and removal rate of greenhouse gases in the atmosphere would also come into play.

that the declining time profile of the resource tax would be preserved, with the third-period resource tax being lower than the second-period tax. Furthermore, the price path of the resource would now be $p_3 = (1+\rho_2)p_2 = (1+\rho_2)(1+\rho_3)p_1$, where ρ_2 and ρ_3 denote the second- and third-period interest rates, respectively, and p_3 the market price of the resource in the third period. Imposing a strictly positive capital tax in the second period like in the two-period model in addition to resource taxes would lower production and thus income and savings of the representative household in that period. As a result, the third-period capital stock would be lower, thereby increasing ρ_3. It seems plausible that this is not in the governments' best interest since it would make second-period resource extraction more attractive. Therefore, I conjecture that capital would also be taxed at a strictly positive rate in the third period to bring ρ_3 down, and possibly at an even higher rate than in the second period in order to flatten the price and extraction path over time. If the indirect effect of increasing ρ_3 is larger than the direct effect of bringing ρ_2 down, the second-period capital tax might be negative. However, the direct effect should outweigh the indirect effect.

I have assumed that the government disposes of a commitment technology in this model but this assumption is not innocuous. The open-loop Nash equilibrium derived here is time-inconsistent as governments would want to deviate from their announced policies once the second period has arrived. In particular, they would like to levy zero taxes on second-period investment and resource use. The intuition is that the environmental externality which is the only reason for taxation in the model results from first-period resource use and thus cannot be addressed anymore in the second period. Such time-inconsistencies are not only a phenomenon of multi-country models like in this paper. They also haunt the literature on dynamic capital (income) taxation in closed economies. As pointed out by Fischer (1980) and Chamley (1986), a benevolent government finds it optimal to tax capital heavily in the short-run but promise zero capital taxes in the long-run in order to encourage investment. However, if future governments can revise these policies, they would optimally deviate from the announced plan and tax capital income heavily in their current and subsequent periods. The intuition is that taxing capital income is more distortionary in the long-run than in the short-run.

A straightforward solution to the time-inconsistency problem in this paper is to drop any second-period policies and introduce another instrument in the first period: a subsidy to savings. In the symmetric equilibrium I examine a second-period tax on capital and a subsidy on savings are equivalent since investment in each country equals the country's savings and the effects of both instruments on the interest rate are the same: they lower it and thus induce substitution out of capital into resources in the second period, which, in turn, slows down resource extraction in the first period. The aim of the above analysis is to illustrate that other policies than taxes on resource owners' capital income are also able to flatten the extraction path by lowering the interest rate – despite the competition for mobile capital and resources which would more generally call for subsidies in the absence of any revenue requirements by the government.

7 Conclusion

This paper has analyzed, in a two-period general equilibrium model, strategic tax-setting of governments which compete for mobile resources and mobile capital and care about the speed of resource extraction. I found that unilateral policies are effective in slowing down resource extraction and that Green Paradox effects arise. Furthermore, factor mobility has been found to aggravate transfrontier pollution problems because governments influence via their tax policies the tax bases in other countries. These private income externalities unambiguously go in the same direction as the environmental externality (at least in aggregate). Moreover, under commitment, governments have been found to have an incentive to tax capital in the future at a strictly positive rate due to the capital-tax-interest-rate channel even though no physical public goods are provided.

The capital-tax-interest-rate channel has so far been neglected in the literature on interjurisdictional competition because strategic interactions between governments have been cast in partial equilibrium frameworks, specifically without a global resource market (Oates and Schwab, 1988; Ogawa and Wildasin, 2009; Eichner and Runkel, 2012).

As the symmetric set-up leads to zero net resource and capital flows across borders, I explore asymmetries with respect to resource or capital endowment in a companion paper. An asymmetric setting incorporates the incentive for resource-importing countries to tax away resource exporters' Hotelling rents.

Appendix

A.1 Derivation of comparative statics

Totally differentiating the first-order conditions (3)–(5) for all $i = 1, \ldots, n$ yields:

$$f_{rr} dr_1^i - d\tau_1^i = dp_1 \ , \tag{A.1}$$

$$F_{kr}dk^i + F_{rr}dr_2^i - d\tau_2^i = dp_2 \ , \tag{A.2}$$

$$F_{kk}dk^i + F_{kr}dr_2^i - d\kappa^i = d\rho \ . \tag{A.3}$$

For notational convenience, all functional dependencies for f_r, f_{rr}, F_{kk}, F_{rr}, F_{kr} and thus Γ, Φ, Ω, Θ and Δ have been dropped. Only in the symmetric equilibrium are the functional values in all countries equal because all arguments have equal size.

Solving (A.1)–(A.3) for dr_1^i, dr_2^i and dk^i, we obtain:

$$dr_1^i = \frac{1}{f_{rr}}(dp_1 + d\tau_1^i) \ , \tag{A.4}$$

$$dr_2^i = \frac{F_{kk}}{\Gamma}\left[dp_2 + d\tau_2^i - \frac{F_{kr}}{F_{kk}}(d\rho + d\kappa^i)\right] \ , \tag{A.5}$$

$$dk^i = \frac{F_{rr}}{\Gamma}\left[d\rho + d\kappa^i - \frac{F_{kr}}{F_{rr}}(dp_2 + d\tau_2^i)\right] \ . \tag{A.6}$$

Denoting $w_1^i \equiv \pi_1^i + \Pi_1^i + \psi_1^i$, we have:

$$dw_1^i = p_1(dq_1^i - dr_1^i) + f_r dr_1^i \ , \tag{A.7}$$

which is needed for determining the reaction of savings to changes in income induced by tax changes. Although $dq_1^i - dr_1^i$ is undefined for any country i, in aggregate it holds:

$$\sum_{l=1}^{n}(dq_1^l - dr_1^l) = 0 \ . \tag{A.8}$$

Totally differentiating Hotelling's rule (7) and the capital and resource market equilibrium conditions (16)–(18), using (A.7) and (A.8), yields:

$$dp_2 = (1+\rho)dp_1 + p_1 d\rho \ , \tag{A.9}$$

$$\sum_{l=1}^{n} dk^l = \sum_{l=1}^{n}\frac{\partial s^l}{\partial \rho}d\rho + \sum_{l=1}^{n}\frac{\partial s^l}{\partial w_1^l}dw_1^l = \sum_{l=1}^{n}\frac{\partial s^l}{\partial \rho}d\rho + \sum_{l=1}^{n} f_r dr_1^l \ , \tag{A.10}$$

$$\sum_{l=1}^{n} dr_1^l = -\sum_{l=1}^{n} dr_2^l \ . \tag{A.11}$$

Starting from a symmetric equilibrium and inserting (A.4)–(A.6) into (A.10) and (A.11), we can write:

$$\frac{nf_r}{f_{rr}}dp_1 + \frac{nF_{kr}}{\Gamma}dp_2 - \frac{n\left[F_{rr} - \frac{\partial s}{\partial \rho}\Gamma\right]}{\Gamma}d\rho + \sum_{l=1}^{n}\frac{f_r}{f_{rr}}d\tau_1^l + \sum_{l=1}^{n}\frac{F_{kr}}{\Gamma}d\tau_2^l - \sum_{l=1}^{n}\frac{F_{rr}}{\Gamma}d\kappa^l = 0 \ , \tag{A.12}$$

$$\frac{n}{f_{rr}}dp_1 + \frac{nF_{kk}}{\Gamma}dp_2 - \frac{nF_{kr}}{\Gamma}d\rho + \sum_{l=1}^{n}\frac{1}{f_{rr}}d\tau_1^l + \sum_{l=1}^{n}\frac{F_{kk}}{\Gamma}d\tau_2^l - \sum_{l=1}^{n}\frac{F_{kr}}{\Gamma}d\kappa^l = 0 \ , \tag{A.13}$$

Finally, by inserting (A.9) into (A.12) and (A.13), it follows:

$$\frac{(1+\rho)F_{kr}}{\Gamma}dp_1 - \frac{F_{rr} - \frac{\partial s}{\partial \rho}\Gamma - p_1F_{kr}}{\Gamma}d\rho - \frac{1}{n}\left[\sum_{l=1}^{n}\frac{F_{rr}}{\Gamma}d\kappa^l - \sum_{l=1}^{n}\frac{F_{kr}}{\Gamma}d\tau_2^l\right] = 0 \ , \tag{A.14}$$

$$\frac{\Gamma + (1+\rho)f_{rr}F_{kk}}{F_{rr}\Gamma}dp_1 + \frac{p_1F_{kk} - F_{kr}}{\Gamma}d\rho + \frac{1}{n}\left[\sum_{l=1}^{n}\frac{1}{f_{rr}}d\tau_1^l + \sum_{l=1}^{n}\frac{F_{kk}}{\Gamma}d\tau_2^l - \sum_{l=1}^{n}\frac{F_{kr}}{\Gamma}d\kappa^l\right] = 0 \ . \tag{A.15}$$

These two equations jointly determine the market reactions $dp_1/d\Box^i$ and $d\rho/d\Box^i$ to unilateral marginal increases in $\Box = \tau_1, \tau_2, \kappa$ in country i, where a unilateral increase in τ_1^i, for example, is found by setting $d\tau_2^i = d\kappa^i = 0$ and $d\tau_1^k = d\tau_2^k = d\kappa^k = 0$ for all $k \neq i$. Inserting these results into (A.9) implies $dp_2/d\Box^i$.

Plugging the market reactions as described by (19a)–(19c) and (22a)–(22c) back into (A.4)–(A.6) for the tax-increasing country i and country $j \neq i$, we obtain after some rearrangements equations (20a)–(21c) and (23a)–(24f).

A.2 Proof of Lemma 2

We know that aggregate resource use in the first period is – for given taxes in all other countries – a function of τ_1^i and τ_2^i. Totally differentiating $r_1 = G(\tau_1^i, \tau_2^i)$ yields:

$$dr_1 = \frac{\partial G}{\partial \tau_1^i}d\tau_1^i + \frac{\partial G}{\partial \tau_2^i}d\tau_2^i \ . \tag{A.16}$$

We also know from the comparative statics that

$$\frac{\partial r_1}{\partial \tau_1^i}\bigg|_{d\tau_2^i=0} = -(1+\rho)\frac{\partial r_1}{\partial \tau_2^i}\bigg|_{d\tau_1^i=0} . \tag{A.17}$$

From these two equations follows immediately:

$$\frac{\partial G}{\partial \tau_1^i} = -(1+\rho)\frac{\partial G}{\partial \tau_2^i} \quad \Leftrightarrow \quad \frac{\partial G}{\partial \tau_1^i} + (1+\rho)\frac{\partial G}{\partial \tau_2^i} = 0 , \tag{A.18}$$

which is a partial differential equation.
Let $G(\tau_1^i, 0) = G(\tau_1^i)$ for $\tau_2^i = 0$. If $G(\tau_1^i)$ exists and is differentiable, then it follows from the calculus of partial differential equations:

$$G(\tau_1^i, \tau_2^i) = G\left(\tau_1^i - \frac{\tau_2^i}{1+\rho}\right) . \tag{A.19}$$

That is, aggregate first-period resource use and thus pollution only depend on the difference $\tau_1^i - \tau_2^i/(1+\rho)$. □

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