ESSAYS ON ENVIRONMENTAL POLICY IN A POLITICALLY MOTIVATED WORLD

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To my parents

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Preface

Anthropogenic climate change has been termed the biggest externality of mankind ever (Stern, 2007). Its effects are global in nature and due to the burning of fossil fuels such as coal, gas and oil. The problems associated with global warming have been widely discussed and need not be repeated in this dissertation. However, the use of fossil fuels in production and consumption causes various other externalities. These range from purely local damage such as urban air pollution through smog or the adverse environmental effects of mountaintop removal mining to global externalities that may have been underestimated so far. The latter include damages caused by oil-based polymers known as plastics. Recent research suggests that $40 - 80\%$ of mega- and macro-marine debris is non-biodegradable plastic (Derraik, 2002). Mechanical forces and photochemical processes trigger its breakdown into microplastics which pose a serious threat to wildlife and humans (Moore, 2008).

Despite these pressing environmental issues, countries' willingness to cooperate across borders in order to reduce environmental damage has been limited. For instance, the climate talks (Conferences of Parties, in short COPs) organized under the umbrella of the United Nations Framework Convention on Climate Change have not reached binding reduction targets for greenhouse gas emissions. From an economic point of view, this is not surprising since emissions reductions are contributions to the provision of the global public good 'climate stabilization'. As the social costs of its provision exceed its private costs, economic theory suggests that inefficiently high carbon emissions will result in equilibrium. Besides this environmental externality, other distortions due to political motives or constraints arise which may improve or worsen environmental quality. Staying with the climate negotiations example, it is well documented that environmental and business lobby groups which are formally accredited as observers to the annual COP, exert influence on policy-makers in various ways (Betzold, 2013). Activities include organizing side events, distributing literature, preparing press releases, serving on government delegations or lobbying delegates from the home country or from other countries (Orr, 2006). The COP in Warsaw in 2013 experienced a huge withdrawal of environment and development groups because they felt that lobbying from fossil fuel companies that partly sponsored the event was impeding progress at the talks.[1]

This dissertation analyzes in the context of environmental and climate policy the incentives faced by politicians who are at least partly self-interested or by welfare-maximizing governments that act strategically. By 'self-interested' politicians, I mean politicians who do not solely maximize the welfare of their electorate. Instead, they are also interested to some degree in maximizing their chances of getting (re-)elected or – in the worst case – in simply collecting bribes. The chances of (re-)election can be increased 1) by raising campaign contributions from special interest groups or 2) by adopting policy platforms that maximize votes. In the first case, incumbent politicians need to take account of the welfare of their electorate as otherwise they may be voted out of office at the next ballot. In exchange for campaign contributions, however, they also grant political favors to stakeholders such as single companies, organizations representing industry, trade or services, labor unions or environmentalist groups, just to name a few. As a result of this monetary influence, policies are usually distorted towards the preferences of the strongest interest group (Grossman and Helpman, 2001) and coincide only incidentally with the first-best outcome. In the second case, the question arises which policy or which set of policies should be chosen by candidates in a representative democracy in order to win an election (electoral competition). One answer is provided by the median voter theorem which originates in Duncan Black's work on majority voting (Black, 1948) and its extension to representative democracy by Anthony Downs (Downs, 1957). In its weak form, it states that under majority voting with exogenously given policy positions by candidates, the candidate that wins the election always gets the vote of the median voter. The reason is that he or she is closest to the median voter's preferred policy and thus closest to the ideal points of more than half of all voters. The strong form suggests that 'the median voter gets exactly what he or she wants – to the extent that the elected candidate delivers on his or her campaign promises' (Congleton, 2004). This holds whenever candidates are free to choose their policy positions in order to maximize votes. For both forms, policies will be distorted unless the median voter's preferences reflect the preferences of the whole society.

Apart from these political motives, policies may also be distorted when governments are benevolent and maximize national welfare. This is the case when countries need to

[1] See, e.g., The Guardian, 2013: Green groups walk out of UN climate talks. Available: http://www.theguardian.com/environment/2013/nov/21/mass-walk-out-un-climate-talks-warsaw [Last accessed: 17 May 2014].

rely on the taxation of mobile tax bases such as capital, labor or fossil resources in order to provide a local or global public good. These interactions between countries are the subject of the tax competition literature which goes back to Zodrow and Mieszkowski (1986) and Wilson (1986). In these seminal articles, a physical public good needs to be provided by governments that aim to maximize their residents' utility but take the world market return to capital as given (because the number of countries is very large). Since lump-sum taxes are not available for reasons that lie outside of the model, governments need to resort to taxing capital use by firms. As a source-based tax on capital influences the allocation of capital across countries, governments have an incentive to tax capital at an inefficiently low rate in the Nash equilibrium. The intuition is that they perceive the marginal costs of public good provision to be higher than they indeed are because capital flees the country when the domestic tax is increased. Later contributions to this literature go beyond this perfectly competitive case where governments are price-takers on international markets. Wildasin (1988), e.g., models the large-country case where governments are able to influence world market prices. Some authors subsume the latter scenario under the term 'strategic interaction' (Brueckner, 2003) even though a Nash equilibrium per definition involves some kind of strategic interaction, even in the competitive case. In the context of environmental policy, pollution may spill over from one country to another such that pollution abatement can be regarded as contribution to a transboundary or global public good. As transboundary pollution can mostly be attributed to the use of mobile factors of production, i.e., capital (technology) or fossil resources, welfare-maximizing governments may be induced – similarly to the case of physical public good provision – to deviate from standard textbook-type policies that prescribe internalizing the marginal damage from own consumption or production on own utility.

The first two chapters of this dissertation are concerned with the political economy of environmental policy in a national (Chapter 1) and international (Chapter 2) context. In Chapter 1, the median voter model is employed to analyze ecotax packages and their distributional effects on different generations, using the example of the German ecotax legislation from 1999. Chapter 2 uses the Grossman and Helpman models of lobby group influence (Grossman and Helpman, 1994, 1995a, 1995b) to analyze the formation of international permit markets by non-cooperative governments. Chapters 3 and 4 analyze non-cooperative environmental policies when countries governed by welfare-maximizing policy-makers compete for mobile factors of production and suffer from transboundary pollution. The analysis in Chapter 3 explores decentralized policy-making with mobile capital under the assumptions of perfect complementarity respectively perfect substitutability between capital and emissions in the presence of utility and production externalities. While Chapter 3 is cast in a static partial equilibrium framework, Chapter 4 introduces a second factor of production (resources respectively energy) which is given in finite supply. This chapter is concerned with the interjurisdictional and intertemporal effects of decentralized demand-side climate policies but neglects pollution externalities on production like in Chapter 3.

In the following, I will give a brief overview of the lines of argument developed in each chapter. All chapters are based on stand-alone papers and can be read separately. The respective appendices can be found at the end of each chapter. In Chapters 1 – 3, which are based on co-authored papers, I have kept the pronoun 'we' (as in the published and working paper versions) to clarify that their basis is joint work.

Chapter 1: Intergenerational Aspects of Ecotax Reforms – an Application to Germany

In the first Chapter which is based on joint work with Kerstin Roeder (Habla and Roeder, 2013), a model of overlapping generations and majority voting is developed to analyze an ecotax reform that consists of the tax rate and the budgetary rule. The ecotax revenue can be recycled through a lump-sum transfer or a reduction in pension contributions. In this bi-dimensional policy space, voting cycles may occur which is why we resort to the notion of a 'structure-induced equilibrium' (Kramer, 1972; Shepsle, 1979). For this, we assume two institutions, namely ministries, which have been assigned the power to determine policies in their domain and base their proposals on the median voter's preferences over the issue at stake. In particular, the ministry of the environment proposes a green tax rate for a given share of revenue devoted to the pension scheme, while the ministry of finance suggests a share of ecotax revenue devoted to the pension scheme for a given environmental tax rate. These proposals can be thought of as the best responses (reaction functions) of the respective ministries. Their intersection describes the structure-induced equilibrium of the voting game. Our theoretical results as well as the calibration of our model to the German economy show that the median voter's preferred tax rate may exceed the efficient rate. This holds whenever income of the decisive voter is sufficiently high compared to average income, as rich individuals benefit more from a reduction in pension contributions than they are harmed by an increase in ecotaxes. This is due to the regressive nature of the ecotax. The calibration confirms that the median voter prefers the earmarking of tax revenue for reductions in pension contributions to the alternative lump-sum transfer. This result is quite an accurate prediction of the situation in Germany where 90% of the ecotax revenue are recycled via lowering pension contributions. Furthermore, aging of society as expected for Germany is found to lower the ecotax in the political equilibrium below its optimal level for a constant income distribution.

Chapter 2: Political Influence on Non-cooperative International Climate Policy

In contrast to the first chapter, the analysis in Chapter 2, which is joint work with Ralph Winkler (Habla and Winkler, 2011; Habla and Winkler, 2013), is concerned with the political economy of environmental policy in a multi-country setting. It potentially embodies distortions due to lobbying *and* due to strategic interaction. In particular, we analyze non-cooperative international climate policy in the form of permit markets in a setting of political competition by national interest groups. In the first stage of the model, the two countries under consideration decide whether to link their domestic emission permit markets to an international market, which only forms if it is supported by both countries. In the second stage, countries non-cooperatively decide on the number of tradable emission allowances. In both stages, special interest groups try to sway the government in their favor. We find that (i) both the choice of regime (national vs. international permit markets) and the levels of domestic and global emissions only depend on the aggregate levels of organized stakes in all countries and not on their distribution among individual interest groups, and (ii) an increase in lobbying influence by a particular lobby group may backfire by inducing a change towards the lobby group's less preferred regime. The intuition behind result (i) is that for the determination of the emission levels in the Nash equilibrium with truthful contribution schedules, only the sum of all lobby groups' willingness-to-contribute to the incumbent government matters. If the aggregate willingness-to-contribute does not depend on the distribution of organized stakes as is the case in our model, the same policies will be adopted across all distributions that entail the same national aggregates. Equilibrium contributions, however, will in general differ across distributions. As the choice whether to link national permit markets basically depends on the difference in social welfare plus the lobbies groups' aggregate *gross* utilities between the two regimes, the linking decision is also independent of the distribution of stakes. The intuition for result (ii) goes as follows. Although an increase in the strength of a particular lobby group induces a direct effect in favor of this group's preferred regime in the home country, there are indirect effects due to the strategic interaction of governments on the international level that may counteract the direct effect. In particular, the associated change in equilibrium allowance choices under both regimes may induce one or both countries to change its support away from the lobby group's preferred regime.

Chapter 3: Mobile Capital and Non-cooperative International Environmental Policy

In Chapter 3 which is joint work with Ralph Winkler, we structure the debate whether and to what extent decentralized policies are efficient. To this end, we analyze the interactions of mobile capital and non-cooperative international environmental policy under different sets of assumptions. Modifying the model framework employed by Ogawa and Wildasin (2009) and Eichner and Runkel (2012), we compare the cases when capital and emissions are either perfect complements or perfect substitutes. Like Eichner and Runkel, we allow for an endogenous choice of capital and emissions and stick to the case of symmetric countries. In addition, we account for the possibility that interjurisdictional spillovers do not only impact on the households' utility but may also negatively affect production by lowering the marginal productivity of capital. In case of perfect complementarity between capital and emissions, we find that capital taxes (which are equivalent to taxes on emissions) are inefficiently low in the symmetric Nash equilibrium for a positive capital supply elasticity but set at a strictly positive rate. Even though a unilateral increase of the capital tax lowers pollution and thus increases capital demand in the tax-increasing country through its positive impact on the marginal productivity of capital, the tax increase does not attract investment. This is because investment cannot rise when pollution falls due to their complementary relationship. If capital and emissions are perfect substitutes, they may be addressed separately by policy-makers through a tax on capital *and* a tax on emissions. We show that an increase in the emissions tax and a decrease in the capital tax have the same quantitative effects on global capital use by firms as well as on global pollution. Thus, capital and pollution depend only on the difference in emissions and capital taxes. In the Nash equilibrium, governments may subsidize capital and/or emissions, depending on the size of pollution impacts on production. In contrast to the model with perfect complementarity, a unilateral marginal increase in the tax difference, caused by either an increase of the emissions tax or a decrease in the capital tax, may indeed attract capital *and* lower pollution at the same time. This holds for sufficiently strong pollution impacts on production and incentivizes governments to set an inefficiently high tax difference in equilibrium. We also show that a binding international agreement setting the emissions tax equal to the social marginal damage from emissions eliminates all incentives for capital tax competition.

Chapter 4: Non-Renewable Resource Extraction and Interjurisdictional Competition across Space and Time

Chapter 4 extends the analysis of Chapter 3 in various ways. First, it introduces a finite stock of a non-renewable resource such as fossil oil, coal or gas which will be fully extracted in equilibrium. Second, because of this additional production factor, the model incorporates an intertemporal resource market in addition to the atemporal capital market and is thus cast in a general equilibrium framework. In this two-period model, I analyze non-cooperative demand-side tax policies when symmetric countries compete for capital and resources (energy), both of which are mobile and provided by perfectly competitive markets, while at the same time being concerned with environmental damage from resource use. I find that unilateral increases in resource or capital taxes lead to spatial as well as intertemporal leakage of resource use and thus pollution. If the capital supply elasticity is positive, announcing an increase in future resource taxes gives rise to the effect usually referred to as "Green Paradox" whereas rising future capital taxes may either speed up or slow down resource extraction, depending on the degree of complementarity between capital and resources. For a negative capital supply elasticity, these results may be reversed. The open-loop Nash equilibrium is found to entail inefficiently high resource use in the present (first period) since in addition to the environmental externality, private income externalities arise which go in the same direction. Furthermore, there is an economic rationale to use strictly positive capital taxes under commitment even though there is no revenue requirement by governments. The reason is that in general equilibrium an increase of the capital tax from zero to a strictly positive value unambiguously lowers the world market interest rate. This fall in the interest rate stimulates second-period resource demand in all other countries by inducing a fall in the second-period resource price through the Hotelling rule and by making capital use more attractive. Higher investment also increases resource demand due to the assumed complementarity between capital and resources. As a consequence, first-period resource use and thus pollution go down. I will refer to this channel as the capital-tax-interest-rate channel. In a numerical example, it is shown that this general equilibrium channel is the stronger, the easier it is to substitute capital for resources. The intuition is that a capital tax then leads to a sharper decrease in the interest rate because of the induced substitution and thus causes a stronger increase in second-period resource use. If, by contrast, resources and capital are strong complements, an additional capital tax is not able to significantly lower aggregate first-period resource use. In this case, private income externalities are relatively small compared to the environmental externality.

Chapter 1

Intergenerational Aspects of Ecotax Reforms - an Application to Germany

1.1 Introduction

As part of the growing awareness of environmental problems such as climate change, ecotax reforms have been carried out in many European countries over the course of the last two decades. Beside the environmental benefit of internalizing the externality caused by greenhouse gas emissions, environmental taxes may reap a second 'dividend': the revenue generated by ecotaxes can be recycled as cuts in distortionary taxes such as taxes on labor, entailing welfare gains for the whole economy. This idea, first recognized by Tullock (1967), has given rise to the so-called 'double dividend' hypothesis (see Bovenberg and Goulder, 2002, for an excellent survey).

Germany introduced an ecotax in five steps in yearly intervals between 1999 and 2003. It is levied on transport and heating fuels, natural gas, electricity and, since a change in the law in 2006, also on coal used for heating. A revenue of approximately €18 billion is raised annually, 90% of which is recycled as reductions in pension contributions.[1] Without this share, pension contributions would have to rise by 1.7 percentage points in order to keep pension benefits at their current levels (see Bach, 2009). The ecotax reform turned into a prominent campaign issue for the German parliamentary elections, particularly in 1998 and 2002. Since then the slogan 'Tanken für die Rente' (refuel for old-age pensions) has become a well-known idiom in the German public.[2]

In this paper, we ask how, *under majority voting*, ecotax reforms interact with institutional settings which are already in place and – at least in the short run – unchangeable. Linking ecotaxes to existing systems alters the political equilibrium, as voter coalitions are affected differently by the proposed reform. We take the German policy as a starting point where the size of the pension system is not open to debate, and where the contributors, as compared to the retirees, benefit from the recycling of ecotax revenue. In a similar manner, countries such as the UK, Sweden, Denmark or the Netherlands have adopted ecotax reforms which take pressure from social security systems and the general public budget by cutting social security or personal income taxes (see Bosquet, 2000, for details). We will argue that these ecotax reforms have similar effects when it comes to their political acceptability among voters.

The IPCC (1995)'s highest estimate in the Second Assessment Report for the social cost of carbon amounts to $150 per tonne of carbon, that is, approximately €30 per

[1] The remainder is used for other purposes such as subsidies on renewable energy.

[2] See, e.g., an article on Deutschlandradio in 2004: http://www.dradio.de/dlf/sendungen/hiwi/251994/ [Last accessed: 17 May 2014].

tonne of carbon dioxide (CO_2).[3] While the price of around €6 per tonne of CO_2 in the European Union's emissions trading scheme, as of January 2013, is generally considered too low, the German ecotax on gasoline, for example, is equivalent to an exceptionally high carbon price of €65 per tonne of CO_2.[4] Why is the price of CO_2 implied by the German ecotax so high? We argue that it can be explained by the incentives different generations face under the proposed ecotax package when called to vote. The package consists of the green tax rate and the budgetary rule according to which a fraction of tax revenue is used to finance reductions in pension contributions. The remainder is returned lump-sum. Lump-sum refunding of ecotax revenue, which is sometimes referred to as 'eco-bonus', has been discussed by the Green Party in Germany and was, for example, introduced in Switzerland in 2008 (see Ekins et al., 2008).[5]

Specifically, our model consists of two generations at each point in time – the young and the old. The young work and contribute to the pension scheme whereas the old are retired and enjoy pension benefits. Apart from age, agents differ in their income. They have preferences over two categories of consumer goods – 'non-dirty' and 'dirty' – and the total level of emissions in the atmosphere. A negative consumption externality arises from the consumption of dirty goods such as fossil fuels which cause emissions. All agents alive vote over the tax rate and the refunding rule in each period.

As is well known, the median voter theorem does not apply in multi-dimensional issue spaces like ours if preferences are not single-peaked. We therefore resort to the notion of a 'structure-induced equilibrium' (Kramer, 1972; Shepsle, 1979). It separates the bi-dimensional policy space into single dimensions by assuming that institutions exist which have been assigned the unique power to determine policies related to their field of duties. In our model the ministry of the environment proposes a green tax rate for a *given* share of revenue devoted to the pension scheme, while the ministry of finance suggests a share of ecotax revenue devoted to the pension scheme for a *given* environmental tax rate. These proposals can be thought of as the best responses (reaction functions) of the respective ministries which are based on the median voter's preferences over the issue at stake. Their intersection describes the structure-induced equilibrium of the voting game. In other words, the structure-induced equilibrium

[3] One tonne of carbon has to be multiplied with 11/3 to get CO_2 emissions (IPCC, 2006; p. 1.8).

[4] The ecotax for one liter of gasoline amounts to approximately €0.15, see the website of the German treasury: www.bundesfinanzministerium.de. One liter entails CO_2 emissions of approximately 2.3 kg, yielding a price of €65 per tonne of CO_2. A similar price per tonne of CO_2 applies to diesel, while natural gas is taxed at a lower rate of approximately €18, cf. Bach (2009).

[5] The policy paper by the Green Party can be found here: http://www.gruene-partei.de/cms/default/dokbin/226/226560.diskussionspapier zum oekobonus.pdf.

introduces issue-by-issue voting and retains the median voter approach in a multi-dimensional space. It is also an adequate description of the political arena in Germany.

We compare the political outcome to the ecotax package chosen by a utilitarian social planner and find that the adjusted 'Pigouvian' tax rate internalizes the full marginal damage from the polluting good for all current and future generations, but also accounts for efficiency losses caused by the distortionary nature of pension contributions. Even more surprising, majority voting yields a green tax rate which can be lower *or* higher than the optimal level. The intuition behind this result is as follows: although the social planner internalizes more of the environmental damage due to environmental concerns than individuals, high-income earners benefit more from lowering pension contributions through higher ecotaxes than they are harmed by the tax increase through consumption. This is because young individuals contribute to the pension scheme proportionally to their incomes, while the ecotax rate is regressive. Therefore, if some share of tax revenue is devoted to the pension scheme, the median voter's preferred environmental tax rate will be higher than the adjusted Pigouvian level whenever his income is sufficiently high compared to average income. If, by contrast, all revenue is recycled via lump-sum transfers, the green tax rate in the political equilibrium is more likely to be below its efficient level.

In the calibration of our model to the German economy, we focus on the tax on gasoline as motor fuel expenses constitute the largest share of household expenditure on energy (see Bach, 2009). Our simulations illustrate that the median voter not only prefers all ecotax revenue to cut pension contributions, but also that his income is indeed high enough to raise the politically induced tax rate above its optimal level. Furthermore, we find that a dramatic aging of the population as expected for Germany in the next few decades will lead to lump-sum redistribution of green tax revenue and a politically induced tax rate which is inefficiently low.

Our paper contributes to two strands of literature. On the one hand, it adds to the literature on intergenerational aspects of environmental policy within an Overlapping Generations (OLG) framework (see, *e.g.*, Bovenberg and Heijdra, 1998 and 2002; Karp and Rezai, 2011; or Chiroleu-Assouline and Fodha, 2006). Intergenerational conflicts arise because of different distributional impacts of environmental taxes on the welfare of current generations. This is particularly true for the German ecotax package which is tied to the pension system. On the other hand, the paper contributes to the literature on the political economy of environmental taxation and the double dividend hypothesis. This strand of literature has been developed mainly by Cremer, De Donder and Gahvari in a series of papers. In Cremer et al. (2004), the authors study how a welfare-maximizing government should set the refund rule at the constitutional stage when the ecotax rate is determined in the voting stage and when political competition arises within and between parties. In another paper Cremer et al. (2007) examine the predictions of three political economy models (the Downsian majority-voting approach, the probabilistic-voting model and Roemer (2006)'s model of Party Unanimity Nash Equilibria (PUNE)) with respect to environmental taxes without a refunding rule and compare these predictions to an estimate of US energy taxes. The PUNE concept applied to environmental policy is explored in more detail in Cremer et al. (2008) where the budgetary rule constitutes a further policy instrument. Aidt (2010) studies the impact of industrial lobbying on a green tax package proposed by two competing parties which care about lobby contributions and voters. In his model, the proceeds from the ecotax can be recycled through income tax cuts, extra public spending or tax burden compensation to polluters. Our paper combines both strands of literature in the context of the German ecotax package, treating both the ecotax and the budgetary rule as endogenous. It is, to our knowledge, the first to consider intergenerational aspects of an ecotax package under majority voting.

1.2 The model

1.2.1 The economic environment

Consider an economy with two generations alive: the young (superscript 'Y') and the old (superscript 'O'). Population grows at a constant rate $n > 0$ and the size of the current old is normalized to one. It follows that in every period t for every young person there are $1/(1+n)$ old and the overall size of the population is given by $2+n$. The young are in employment and inelastically supply one unit of labor and earn income $y_{i,t}$. Income is distributed over the support $[y^{-}, y^{+}] \subset \mathcal{R}_{+}$ according to the cumulative distribution function $F(y_t)$. The distribution of income is assumed to have mean $\bar{y}_t$ and to be right-skewed, $F(\bar{y}_t) > 0.5$, implying that median income is below average income. The old are retired and receive pension benefits. The pension scheme is pay-as-you-go (PAYG), that is, the young pay a share b_t of their labor income into the pension scheme and the old get pension benefits $B(y_{i,t-1})$ out of it. Note that in this setup $1/(1+n)$ represents the pensioner/contributor ratio. In Germany the pension scheme is (partly) Bismarckian, i.e., pension benefits positively depend on the agent's prior income, $\partial B(y_{i,t-1})/\partial y_{i,t-1} > 0$. There is no storage technology, so individuals do not save and solely live off their pension benefits in old age. The economy produces two goods: a non-polluting (non-energy) numéraire good and a polluting (energy-related) good d. The latter is taxed at a rate $\theta_t \in \mathcal{R}$. The consumer price of good d thus amounts to $q_t = p_t + \theta_t$. We assume that the producer price is equal to one, i.e. $p_t = 1$.[6] Aggregate consumption of the polluting good is:

$$D_t = (1+n)\int_{y^-}^{y^+} d_{i,t}^Y \mathrm{d}F(y_t) + \int_{y^-}^{y^+} d_{i,t}^O \mathrm{d}F(y_{t-1}) \ . \tag{1.1}$$

Variation in a single individual's consumption of the dirty good $d_{i,t}^j$ $(j = Y, O)$ does not have an impact on overall consumption D_t as the mass of one individual is close to zero. The polluting good causes emissions $E_t = \sum_{x=0}^{t} (1-\delta)^{t-x} D_x$ which bring about disutility $h(E_t)$, with $h' \equiv \phi > 0$ and $h'' = 0$. The stock in period t is given by current pollution and aggregate pollution from previous periods, reduced by the natural decay and removal rate $\delta \in [0;1]$ per period which we assume to be exogenous over time. One can think of the polluting good as fossil fuels whose consumption generates CO_2 and contributes to global warming. A decay rate equal to unity implies that pollution does not accumulate in the atmosphere.

Consumers have Gorman-polar preferences. That is, indirect utilities of a young and old individual-i read as follows:

$$v_{i,t}^Y(q_t, q_{t+1}) = a(q_t) + c(q_t) I_{i,t}^Y - h(E_t) + \rho v_{i,t+1}^O(q_t, q_{t+1}) \ , \tag{1.2}$$

$$v_{i,t}^O(q_t) = a(q_t) + c(q_t) I_{i,t}^O - h(E_t) \ , \tag{1.3}$$

where $\rho \leq 1$ is the utility discount factor and $I_{i,t}^Y$ and $I_{i,t}^O$ are disposable incomes of the two generations. The functions $a(q_t)$ and $c(q_t)$ are positive and satisfy: $a'(q_t) \leq 0$ and $c'(q_t) \leq 0$. Observe that for $c'(q_t) = 0$, preferences are quasi-linear. Disposable incomes of a young and an old agent are given by:

$$I_{i,t}^Y = (1 - b_t) y_{i,t} + \tau_t \ , \tag{1.4}$$

$$I_{i,t}^O = B(y_{i,t-1}) + \tau_t \ , \tag{1.5}$$

where τ_t denotes a lump-sum transfer or eco-bonus financed by taxation of the polluting good. As pension benefits in PAYG systems are usually lower than pre-retirement earnings, we assume that $I_{i,t}^Y \geq I_{i,t}^O$ for $y_i \in (y^-, y^+]$. Furthermore, $I_{i,t}^Y = I_{i,t}^O$ for $y_i = y^-$ as the state provides social welfare assistance to everyone below the minimum

[6] We carry out a partial equilibrium analysis which abstains from price and wage effects. Equivalently, we could assume that the two goods are produced by a linear technology subject to constant returns to scale in a competitive environment.

subsistence level. By Roy's identity, the demand for the polluting good (expressed as a function of θ_t as $p_t = 1$) is:[7]

$$d_i^j(\theta_t) = -\frac{\partial v_{i,t}^j / \partial q_t}{\partial v_{i,t}^j / \partial I_{i,t}^j} = -\frac{a'(q_t) + c'(q_t) I_{i,t}^j}{c(q_t)} \ , \quad j = Y, O \ . \tag{1.6}$$

Except in the limiting case of quasi-linear preferences, $c'(q_t) = 0$, demand for the energy-related good is increasing in individuals' income. Nevertheless, expenditure shares of polluting goods decrease at all income deciles as income increases (Poterba, 1991). This regressive nature of ecotaxes has also been verified for Germany by Bach (2009).

1.2.2 The economic equilibrium

In an economic equilibrium, public budgets need to be balanced. Revenue from taxation of the polluting good is given by $\theta_t D(\theta_t)$. A share $\alpha_t \in [0;1]$ of this revenue and pension contributions by the young have to finance pension benefits of the old. To account for the distortionary nature of pension contributions, we assume that a fraction $\eta < 1$ of pension contributions is lost during the redistributive process (e.g., Galasso and Profeta, 2007; Cremer et al., 2008). This deadweight loss is larger the less are pension benefits earnings-related (e.g., Conde-Ruiz and Profeta, 2007).[8] The budget constraint of the pension scheme thus amounts to:

$$(1+n)(1-\eta) b_t \int_{y^-}^{y^+} y_{i,t} \mathrm{d}F(y_t) + \alpha_t \theta_t D(\theta_t) = \int_{y^-}^{y^+} B(y_{i,t-1}) \mathrm{d}F(y_{t-1}) \ . \tag{1.7}$$

Total pension entitlements of the current old in period t are fixed and, thus, the pension contribution rate adjusts to satisfy the above budget constraint.[9] Specifically, the pension contribution rate which balances pension benefits and tax revenue can be

[7] Note that this preference specification implicitly assumes that the consumer has some exogenous income such as social welfare aid or assets so that his demand for the polluting good is positive even if $I_{i,t}^j = 0$.

[8] The deadweight loss η is related to the Marginal Cost of Public Funds (MCF) for the pension system through $\eta = 1 - c(q_t)/\text{MCF}$, that is, a higher MCF goes hand in hand with a higher deadweight loss (see Kleven and Kreiner, 2006, p. 1960, for the definition of MCF). In the following, we will therefore use the two expressions synonymously.

[9] Since the pension scheme is PAYG, pension entitlements are determined by an implicit intergenerational contract, see, e.g., Hammond (1975; pp. 121-124).

expressed as:

$$b_t(\theta_t, \alpha_t) = \frac{\bar{B}_t - \alpha_t \theta_t D(\theta_t)}{(1+n)(1-\eta)\bar{y}_t} \ , \tag{1.8}$$

where $\bar{B}_t \equiv \int_{y^-}^{y^+} B(y_{i,t-1}) \mathrm{d}F(y_{t-1})$. To see how a higher pollution tax rate affects the pension contribution rate – given pension benefits $B(y_{i,t-1})$ for all i are kept constant – we have to determine the sign of the following derivative:[10]

$$\frac{\partial b_t(\theta_t, \alpha_t)}{\partial \theta_t} = \frac{-\alpha_t \Big(D(\theta_t) + \theta_t D'(\theta_t) \Big)}{(1+n)(1-\eta)\bar{y}_t} \ . \tag{1.9}$$

The above expression is negative whenever

$$D(\theta_t) + \theta_t D'(\theta_t) = D(\theta_t)(1 - \varepsilon_{D,\theta}) > 0 \ , \tag{1.10}$$

where $\varepsilon_{D,\theta} = -D'(\theta_t)\theta_t / D(\theta_t)$ is the demand elasticity of the polluting good with respect to the tax rate. In other words, whenever consumption of the polluting good is inelastic, that is, smaller than one, the pension contribution rate decreases with the green tax rate. The intuition behind it is straightforward. If a one percent increase in the green tax rate leads to a decrease in the aggregate consumption of the dirty good by less than one percent, a positive revenue from taxation is generated. This revenue can be used to reduce the pension contribution rate while keeping pension benefits constant. In the following, we will assume that $\varepsilon_{D,\theta} < 1$.[11]

The share $1 - \alpha_t$ of revenue from environmental taxation is employed to finance the lump-sum transfer τ_t to each individual – the young and the old. Thus, we have:

$$(1 - \alpha_t)\theta_t D(\theta_t) = (2+n)\tau_t \quad \Leftrightarrow \quad \tau_t(\theta_t, \alpha_t) = \frac{1 - \alpha_t}{2+n} \theta_t D(\theta_t) \ . \tag{1.11}$$

Inserting expressions (1.8) and (1.11) back into the indirect utility function of the

[10] As the monthly pension contributions in Germany are shared equally between employer and employee, the benefits of a higher ecotax – if tax revenue is at least partly devoted to the pension scheme – accrue to both. In our model, we assume that each agent is at the same time employee and shareholder in the employer's firm so that he fully and solely benefits from the reduction in pension contributions. This is equivalent to assuming that the tax incidence falls on the employee.

[11] Our assumption on $\varepsilon_{D,\theta}$ is confirmed by several studies which estimate long-run price elasticities of energy demand, see e.g. Hunt and Manning (1989) or Small and Van Dender (2007). Estimates range between 0.1 and 0.9 for different sources of energy.

young yields their reduced indirect utility function:

$$V_{i,t}^{Y}(\theta_t,\alpha_t) = \quad a(q_t) + c(q_t)\left[\left(1 - \frac{\bar{B}_t - \alpha_t\theta_t D(\theta_t)}{(1+n)(1-\eta)\bar{y}_t}\right) y_{i,t} + \frac{1-\alpha_t}{2+n}\theta_t D(\theta_t)\right] \\ - h(E(\theta_t)) + \rho V_{i,t+1}^{O}(\theta_t) \ , \tag{1.12}$$

where $V_{i,t+1}^{O}(\theta_t)$ denotes indirect utility of a currently young person in old age which, for $\delta < 1$, depends on the current green tax rate through the stock of pollution in the atmosphere. However, it is independent of the share of taxes devoted to the pension scheme in period t as this share does not affect any future budgets.[12] The old's reduced indirect utility function is given by:

$$V_{i,t}^{O}(\theta_t,\alpha_t) = a(q_t) + c(q_t)\left(B(y_{i,t-1}) + \frac{1-\alpha_t}{2+n}\theta_t D(\theta_t)\right) - h(E_t) \ . \tag{1.13}$$

The above reduced indirect utility functions of an i-type young and old person can be used to express their preferences for the green tax rate θ_t and the share of tax revenue devoted to the pension scheme, α_t, in an economic equilibrium. Both policy variables are specified in the political process described in Section 1.4.

1.3 Social optimum

This section analyzes the optimal green tax rate and share of environmental taxes devoted to the pension scheme chosen by a utilitarian social planner. It provides a benchmark against which the properties of the political outcome can be assessed.

At time t, the social planner accounts for the welfare of all generations from t to infinity, that is, for the current old plus all current and future young generations.[13] Using equations (1.12) and (1.13), the welfare function can be written as a function of

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[12] Specifically, $V_{i,t+1}^{O}(\theta_t) = a(q_{t+1}) + c(q_{t+1})\left(B(y_{i,t}) + \frac{1-\alpha_{t+1}}{2+n}\theta_{t+1}D(\theta_{t+1})\right) - h(E(\theta_t,\theta_{t+1}))$. Also note that we employ a shortcut in our notation. Although the young's utility depends on the tax rate in $t+1$ (and all past tax rates through the stock of emissions), we express it as a function of time t policy variables only.

[13] We do not distinguish between private discount rates used by one generation to discount their remaining lifetime utility and the social discount rate at which the social planner trades off the weighted lifetime utility of different generations. See Schneider et al. (2012) on intergenerational trade-offs in models with an infinitely-lived agent and OLG models.

the policy variables of time t:

$$\mathcal{W}_t(\theta_t, \alpha_t) = \int_{y^-}^{y^+} V_{i,t}^O(\theta_t, \alpha_t)\mathrm{d}F(y_{t-1}) + (1+n)\sum_{x=t}^{\infty}\Big((1+n)\rho\Big)^{x-t}\int_{y^-}^{y^+} V_{i,x}^Y(\theta_t, \alpha_t)\mathrm{d}F(y_x) \ . \tag{1.14}$$

Note that with a utilitarian welfare function and Gorman-polar preferences, redistributive considerations within and between generations do not matter – all agents have a constant marginal utility of income equal to $c(q_t)$. We assume that the size of the pension system is not open to debate. In other words, the social planner is tied to an implicit contract among successive generations, in which today's young agree on a transfer to current retirees. The young generation, in turn, expects to be rewarded with a corresponding transfer in their old age.

Differentiating equation (1.14) with respect to α_t yields:

$$c(q_t)\frac{\eta}{1-\eta}\theta_t D(\theta_t) > 0 \quad \Rightarrow \quad \alpha_t^* = 1 \ . \tag{1.15}$$

From a normative perspective it is, thus, optimal to devote all revenue generated by environmental taxation to the pension scheme. The reason is that a reduction in the pension contribution rate goes hand in hand with a lower deadweight loss compared to a lump-sum redistribution of environmental tax revenue. This is equivalent to the 'weak' version of the double dividend hypothesis (see, e.g., Goulder, 1995). It states that passing on tax revenue through cuts in distortionary taxes entails a welfare gain, independent of environmental considerations.

Contrary to α_t, the tax rate in period t continues to have an effect on all future generations through consumption of the dirty good in that period and the associated change in the stock of emissions for $\delta < 1$. The first-order condition of (1.14) with respect to θ_t is – after some rearrangements and using equation (1.6) – given by:[14]

$$-D(\theta_t) + D(\theta_t)(1-\varepsilon_{D,\theta})\left(1 + \frac{\eta\alpha_t}{1-\eta}\right) - \frac{2+n}{1-z}\frac{\phi D'(\theta_t)}{c(q_t)} = 0 \ , \tag{1.16}$$

where $z \equiv \rho(1+n)(1-\delta)$ and $\rho(1+n) < 1$ for the infinite sum of marginal damages to converge to a constant value. The first term captures aggregate marginal costs of green taxes in terms of consumption in period t. The second term reflects the marginal benefits of higher tax revenue. Revenue from environmental taxation is worth more

[14] The second-order condition with respect to θ_t, SOC_θ^*, is assumed to be strictly negative. For a more detailed derivation of the social optimum and the second-order condition see the Appendix.

the more is devoted to the pension scheme, as this reduces the existing deadweight loss of pension contributions. The last expression mirrors the reduction in marginal social costs inflicted on all currently living and future generations when overall consumption of the polluting good declines due to a tax increase in period t.[15] Note that $\partial\theta_t^*/\partial\alpha_t > 0$, that is, the socially efficient tax rate is higher the more tax revenue is devoted to the pension scheme.

Rearranging equation (1.16) and considering that $\alpha_t^* = 1$, we have:

$$\theta_t^* = \frac{(2+n)(1-\eta)\phi\varepsilon_{D,\theta}}{c(q_t)(1-z)(\varepsilon_{D,\theta}-\eta)} \ , \tag{1.17}$$

which for non-distortionary pension contributions, $\eta = 0$, and no stock pollution, $\delta = 1$, is the standard first-best Pigouvian tax rule: $\theta_t^* = (2+n)\phi/c(q_t)$. That is, the optimal green tax rate θ_t^* should be chosen to equal the marginal social damage of the externality. In the second-best, i.e. $\eta > 0$, the optimal tax rate is additionally adjusted by the marginal costs of public funds and the demand elasticity for the dirty good. As intuition suggests, higher marginal costs of public funds in the pension scheme increase the attractiveness of green taxes, whereas a higher demand elasticity of the polluting good makes its taxation less appealing. In our OLG framework, an extra term shows up for $\delta < 1$ as compared to e.g. Cremer et al. (2008): the optimal green tax rate also accounts for the present value of marginal damages inflicted on all current and future generations, $\phi/(1-z)$. For the green tax rate to be positive, we require $\varepsilon_{D,\theta} > \eta$.[16]

1.4 Majority voting

In the following we analyze the majority voting process. In each period, the young and old vote on the green tax rate θ_t and on the share of tax revenue devoted to the pension scheme α_t (repeated voting) and they do so sincerely. Agents' preferences over the two policy variables are aggregated through a political system of majoritarian voting. Each individual has zero mass, so that no individual vote can change the outcome of the election.

We examine structure-induced equilibria where agents vote simultaneously but separately on the issues at stake. This idea was developed independently by Kramer

[15] Since ϕ is constant, the first-order condition is independent of all future emissions and hence all future environmental tax rates.

[16] We can assume that this condition holds as it is well-known in the literature that Bismarckian pension schemes bring about a low η (e.g., Conde-Ruiz and Profeta, 2007).

(1972) and Shepsle (1979).[17] In particular, the political system is characterized by the following institutional arrangement. An elected government perfectly represents the preferences of the whole electorate – the young and old. The policy issues at stake are assigned to perfectly representative ministries. The share of tax revenue devoted to the pension scheme is determined by the ministry of finance, while the ministry of the environment is accountable for the green tax rate. In particular, the ministry of environment proposes an ecotax rate for a *given* share of revenue devoted to the pension scheme. Likewise, the ministry of finance suggests a share of revenue devoted to the pension scheme for a *given* environmental tax rate. Proposals are rooted in the median voter's preferences over the issue at stake, and can be thought of as the best responses or reaction functions of the ministries. Their intersection characterizes the structure-induced equilibrium of the voting game where policy proposals of the ministries are mutual best responses to one another. The structure-induced equilibrium thus introduces issue-by-issue voting and retains the median voter approach in a multi-dimensional issue space.

This institutional setting is a good description of the German political system where we can observe the same chain of delegation: from voters to elected representatives; from the legislative body (the parliament) to the executive branch, specifically to the head of government (the Chancellor); from the Chancellor to the heads of different executive departments who are – by the German constitution – given the right to carry out their duties independently within the boundaries set by the Chancellor's political directive (principle of departmentalization, 'Ressortprinzip'); and finally from the cabinet ministers to civil servants (see, e.g., Schnapp, 2001; Strøm, 2000).

Section 1.4.1 specifies every voter's ideal point over the share of tax revenue devoted to the pension scheme for every given tax rate, $\alpha_t(\theta_t)$, followed by the derivation of the preferred environmental tax rate for every given share devoted to the pension scheme, $\theta_t(\alpha_t)$, in Section 1.4.2. At the end of each section, the median voter over α_t and θ_t is identified. Section 1.4.3 determines the structure-induced equilibrium of the voting game.

[17] Alternatively, our setting could be framed such that decisions are taken sequentially. The natural first stage would then be the decision on the ecotax rate while the utilization of tax revenue would be determined in the second stage. As will be shown later, the share of ecotax revenue devoted to the pension scheme in the political equilibrium is independent of θ_t (it only depends on the income of the median voter). Therefore, the outcome of the sequential game coincides with the Kramer-Shepsle equilibrium we describe.

1.4.1 The budgetary rule

The young. The young generation finds their preferred share of green tax revenue devoted to the pension scheme by maximizing indirect utility, equation (1.12), with respect to α_t. Individual-i's first-order condition amounts to:

$$c(q_t)\theta_t D(\theta_t)\left(\frac{y_{i,t}}{(1+n)(1-\eta)\bar{y}_t} - \frac{1}{2+n}\right) \gtreqless 0 \ . \tag{1.18}$$

The above expression can be positive or negative. It is positive if the benefit due to lower pension contributions (first term in brackets) exceeds the benefit of a lump-sum transfer (second term). Since contributions into the pension scheme are proportional to income, the advantage of lower pension contributions over the eco-bonus increases with income. Assume, for example, that green taxes reduce the pension contribution rate by 2 percentage points, then 2 percent of €1,000 are obviously less than 2 percent of €2,000. The critical income $\tilde{y}_t$ below which a young individual prefers that all green tax revenue is given back in a lump-sum way is defined by:

$$\tilde{y}_t \equiv \frac{1+n}{2+n}(1-\eta)\bar{y}_t \ . \tag{1.19}$$

For an individual with income $\tilde{y}_t$, the return of a lump-sum redistribution, $1/(2+n)$, is just as high as the return of a reduction in pension benefits, $\tilde{y}_t/[(1+n)(1-\eta)\bar{y}_t]$.

The young's preferred share of environmental taxes devoted to the pension scheme is thus given by:

$$\begin{aligned} \alpha_t^Y(\theta_t) &= 0 \qquad \text{if} \qquad y_{i,t} < \tilde{y}_t \ , \\ \alpha_t^Y(\theta_t) &= 1 \qquad \text{if} \qquad \tilde{y}_t \ \leq y_{i,t} \ . \end{aligned} \tag{1.20}$$

The old. Maximizing the old's indirect utility function, equation (1.13), with respect to α_t, yields the following first-order condition:

$$-\,c(q_t)\frac{\theta_t D(\theta_t)}{2+n} < 0 \quad \Rightarrow \quad \alpha_t^O(\theta_t) = 0 \ . \tag{1.21}$$

As the old do not benefit from a reduction in the pension contribution rate, they prefer an eco-bonus – irrespective of the size of the green tax rate.

To sum up our findings in this section, we conclude with the following Lemma.

Lemma 1.1 (Comparison of the old's and young's preferred budgetary rule) *Old individuals and young individuals with low income ($y_{i,t} < \tilde{y}_t$) prefer redistribution of tax revenue via a lump-sum transfer whereas higher income earners ($y_{i,t} \geq \tilde{y}_t$) vote for a reduction of pension contributions.*

Thus, although the weak double dividend would materialize if all tax revenue were refunded through reductions in pensions contributions, as in the social optimum, old individuals and young individuals with low income benefit more from lump-sum replacement of tax revenue and will therefore not support revenue recycling via the pension scheme.

Voters can be ordered according to age and income. As long as $n > 0$, it follows that there are always more working agents than retired individuals. This implies that the median voter – the pivot in determining the political outcome of majority voting – is a young type-i individual who divides the electorate in half. Specifically, the median voter is determined through:

$$1 + (1+n)F(y^{\alpha}_{M,t}) = \frac{2+n}{2} \quad \Leftrightarrow \quad F(y^{\alpha}_{M,t}) = \frac{n}{2(1+n)} \; . \tag{1.22}$$

From the above equation it can be easily verified that a lower population growth rate goes hand in hand with a lower income of the median voter.

1.4.2 The green tax rate

The young. Young individuals find their preferred green tax rate $\theta^{Y}_{i,t}$ for a given α_t by maximizing their indirect utility function (1.12) with respect to θ_t. The corresponding first-order condition can be written as:

$$-\, d^{Y}_{i}(\theta_t) + D(\theta_t)(1-\varepsilon_{D,\theta})\left(\frac{\alpha_t y_{i,t}}{(1+n)(1-\eta)\bar{y}_t} + \frac{1-\alpha_t}{2+n}\right) - [1+\rho(1-\delta)]\,\frac{\phi D'(\theta_t)}{c(q_t)} = 0 \; . \tag{1.23}$$

The first term in this equation reflects the individual's direct costs of higher green taxes. The second expression captures the marginal benefit of higher ecotax revenue: the reduction in pension contributions and the higher lump-sum transfer. The third term represents the reduction in the negative externality (for the lifetime of a young individual) due to lower overall pollution, as aggregate consumption of the polluting good decreases with its taxation. The preferred green tax rate by a young individual-i balances these trade-offs. The second-order condition SOC^{Y}_{θ} (specified in the Appendix) is assumed to be negative for preferences to be single-peaked.

To determine the median voter we need to know how the young's preferred environmental tax rate changes in income. With the help of the implicit function theorem, we can establish the following result:

$$\frac{\partial \theta_{i,t}^{Y}}{\partial y_{i,t}} = \frac{c(q_t)}{SOC_{\theta}^{Y}} \left[\frac{\partial d_i^Y(\theta_t)}{\partial y_{i,t}} - \frac{\alpha_t D(\theta_t)(1-\varepsilon_{D,\theta})}{(1+n)(1-\eta)\bar{y}_t} \right] \gtreqless 0 \ . \tag{1.24}$$

If all ecotax revenue is given back lump-sum, i.e. $\alpha_t = 0$, the above equation is always non-positive implying that higher income agents (weakly) prefer a lower ecotax rate. Since consumption of the dirty good (weakly) increases with income, these agents are (weakly) harmed more by green taxes. If, however, ecotax revenue is employed to cut back pension contributions, the result may reverse, implying that higher income individuals prefer higher tax rates. As explained earlier, the advantage of lower pension contributions increases with income. So, whether lower or higher pollution is more desirable for high-income earners does, in our model, not depend on heterogenous preferences concerning the quality of the environment. All individuals are equally hit by pollution. Instead, individuals with different incomes are affected differently by ecotaxes and revenue recycling.[18]

The old. Old agents find their preferred green tax rate $\theta_{i,t}^{O}$ by maximizing their indirect utility function (1.13) with respect to θ_t. The corresponding first-order condition reads as follows:

$$-d_i^O(\theta_t) + \frac{1-\alpha_t}{2+n} D(\theta_t)(1-\varepsilon_{D,\theta}) - \frac{\phi D'(\theta_t)}{c(q_t)} = 0 \ . \tag{1.25}$$

As for the young, the first term reflects the direct costs of higher green taxes. The second expression captures the benefit of green tax revenue if a positive share is given back in a lump-sum fashion while the last term expresses the reduction in the negative externality for the lifetime of an old agent. Again, the second-order condition SOC_{θ}^{O}

[18] There was a maximum determination base (MDB) of €5.300 (€4.500) in the West (East) for pension contributions in Germany in 2008. This implies that agents with monthly incomes higher than the MDB no longer benefit proportionally to income from reductions in pension contributions. Therefore, their preferred ecotax rate does not rise with income anymore as can be seen in equation (1.23). Furthermore, agents with incomes above the MDB have higher disposable incomes which cause them to consume more of the polluting good and tend to lower their desired tax rates (first addend in equation (1.23)).

is assumed to hold for preferences to be single-peaked (see the Appendix). We have

$$\frac{\partial \theta_{i,t}^{O}}{\partial y_{i,t-1}} = \frac{c(q_t)}{SOC_{\theta}^{Y}} \frac{\partial d_i^{O}(\theta_t)}{\partial y_{i,t-1}} \leq 0 \ , \tag{1.26}$$

independently of the budgetary rule. All old individuals are equally (un)affected by the refunding rule. Those with higher income (weakly) consume more of the dirty good and thus have to pay more taxes in absolute terms (except for quasi-linearity). The old's preferred green tax rate thus (weakly) decreases with income.

We are now able to compare the preferred tax rates of the old and young generation and can establish the following Lemma.

Lemma 1.2 (Comparison of the old's and young's preferred tax rates) *Evaluating the old's first-order condition, equation (1.25), at the preferred green tax rate of a young individual-i with the same labor income as the old one period earlier, equation (1.23), yields:*

$$\left.\frac{\partial V_{i,t}^{O}(\theta_t)}{\partial \theta_t}\right|_{\theta_{i,t}^{Y}} \gtreqless 0 \Leftrightarrow d_i^{Y}(\theta_t) - d_i^{O}(\theta_t) - \frac{\alpha_t D(\theta_t)(1-\varepsilon_{D,\theta}) y_{i,t}}{(1+n)(1-\eta)\bar{y}_t} + \rho(1-\delta)\frac{\phi D'(\theta_t)}{c(q_t)} \gtreqless 0 \ . \tag{1.27}$$

As $I_{i,t}^{Y} \geq I_{i,t}^{O}$ for each individual-i with the same labor income in their working lives, an old individual absolutely consumes (weakly) less of the dirty good, $d_i^{Y}(\theta_t) \geq d_i^{O}(\theta_t)$, than a young individual of type-i and thus prefers a higher tax rate. For quasi-linear preferences, this effect drops out. Two other effects may, however, make the young generation prefer a higher green tax rate compared to the old generation. First, the young benefit – for a positive α_t – from the reduction in the pension contribution rate (and the more so the more they earn), whereas pension benefits of the old generation are unaffected by the green tax. Second, the young generation is hit more by environmental damage than the old, because they live longer and incur disutility from the stock of pollution also in the second half of their lives. The latter effect is independent of income. If these two effects are sufficiently strong, the young's preferred tax rate will exceed the old's preferred tax rate.

For $\partial \theta_{i,t}^{Y} / \partial y_{i,t} \geq 0$ (holds for the case with no income effects), agents can be ordered according to their age and income with respect to their preferences over the ecotax rate, as illustrated in Figure 1.1 for the case of quasi-linear preferences. As long as $n > 0$, it follows that there are always more working agents than retired individuals and the median voter is again identified by equation (1.22). For $\partial \theta_{i,t}^{Y} / \partial y_{i,t} < 0$, both

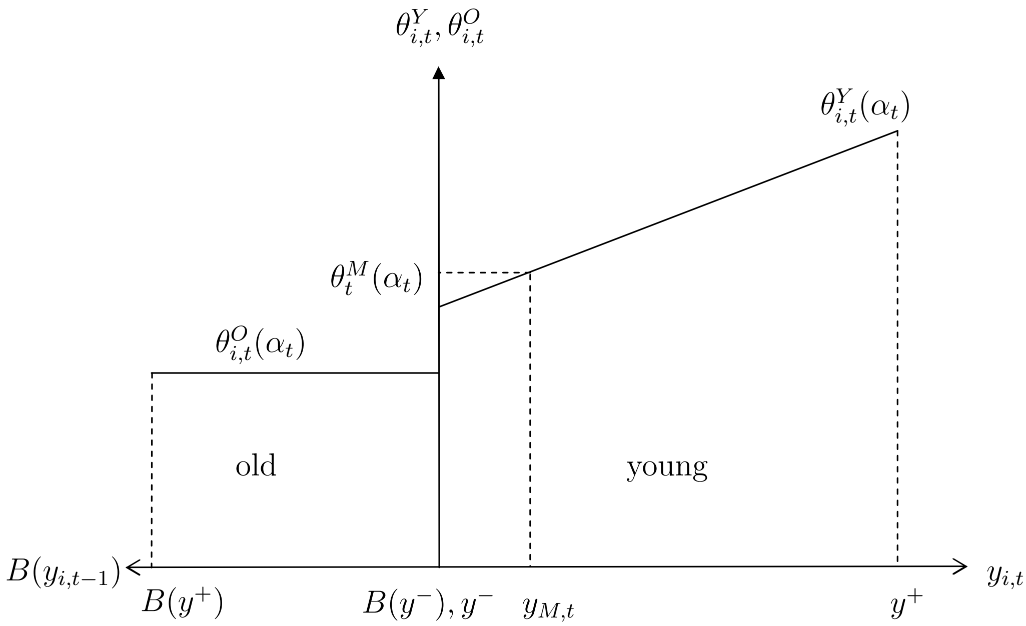

Figure 1.1: Political Equilibrium for $c'(q_t) = 0$ and $\alpha_t > 0$.

generations' preferred ecotax rates decrease with income, and hence, there may be two median voters – a young and an old individual – who prefer the same tax rate (equation (1.27) equal to zero). The following Lemma summarizes the determination of the median voter for both cases.

Lemma 1.3 (The median voter over the green tax rate)
For $n > 0$, the median voter's preferred tax rate always solves the young's first-order condition, equation (1.23). Additionally,

(i) for $\partial\theta^Y_{i,t}/\partial y_{i,t} \geq 0$, the median voter's income is determined by

$$1 + (1+n)F(y_{M,t}) = \frac{2+n}{2} \quad \Leftrightarrow \quad F(y_{M,t}) = \frac{n}{2(1+n)} \ , \tag{1.28}$$

(ii) for $\partial\theta^Y_{i,t}/\partial y_{i,t} < 0$, the median voter can also be both a young and an old agent whose incomes are determined by

$$F(y_{M,t-1}) + (1+n)F(y_{M,t}) = \frac{2+n}{2} \quad \text{and} \tag{1.29}$$

$$d^Y_M(\theta_t) - d^O_M(\theta_t) - \frac{\alpha_t D(\theta_t)(1-\varepsilon_{D,\theta})y_{M,t}}{(1+n)(1-\eta)\bar{y}_t} + \rho(1-\delta)\frac{\phi D'(\theta_t)}{c(q_t)} = 0 \ . \tag{1.30}$$

If the ordering of preferences is such that $F(y^-) + (1+n)F(y_{M,t}) = (2+n)/2$ or $F(y^+) + (1+n)F(y_{M,t}) = (2+n)/2$, the median voter is again solely determined *by a young agent.*[19]

For $\partial\theta^Y_{i,t}/\partial y_{i,t} \geq 0$, the median voter over both dimensions is the same, i.e., $y^\alpha_{M,t} = y_{M,t}$.

1.4.3 The political equilibrium

In the previous sections we identified the median voters for each policy dimension who may or may not be identical. Their incomes are determined by equation (1.22) for the budgetary rule and by Lemma 1.3 for the green tax rate. As argued above, the preferred policies of the median voter(s) – $\theta^M_t(\alpha_t)$ and $\alpha^M_t(\theta_t)$ – can be interpreted as reaction functions. Their intersection yields the structure-induced equilibrium $(\theta^{eq}_t, \alpha^{eq}_t)$.

First, assume the median voter's income is such that $y_{M,t} < \tilde{y}_t$ implying $\alpha^{eq}_t = 0$. The green tax rate in the political equilibrium is then implicitly determined through:

$$- d^Y_M(\theta_t) + \frac{D(\theta_t)(1-\varepsilon_{D,\theta})}{2+n} - [1+\rho(1-\delta)]\,\frac{\phi D'(\theta_t)}{c(q_t)} = 0\ . \tag{1.31}$$

Evaluation of the social planner's first-order condition with respect to θ_t, equation (1.16), at equation (1.31) yields:

$$\left.\frac{\partial \mathcal{W}(\theta_t, \alpha_t = 1)}{\partial \theta_t}\right|_{\theta^{eq}_t, \alpha^{eq}_t = 0} \gtreqless 0 \Leftrightarrow$$

$$d^Y_M(\theta_t) - \bar{d}(\theta_t) + \frac{D(\theta_t)(1-\varepsilon_{D,\theta})\eta}{1-\eta} - \frac{\phi D'(\theta_t)}{c(q_t)}\frac{z(z+n)}{1-z} \gtreqless 0\ . \tag{1.32}$$

As $d^Y_M(\theta_t) \leq \bar{d}(\theta_t)$[20] (holds with equality for quasi-linear preferences), the above equation is indeterminate in sign. While income effects drag the tax rate towards or beyond the social optimum, the other two effects have the opposite impact. If all environmental taxes are given back in a lump-sum fashion, $\alpha^{eq}_t = 0$, the green tax rate chosen in the political process does not account for efficiency losses induced by the pension scheme. The social planner, by contrast, takes into consideration that higher green taxes reduce the deadweight loss caused by pension contributions. Furthermore, for $\delta < 1$ ($\Leftrightarrow z > 0$), he takes the effect of today's pollution on all future generations into account and not only the future damage inflicted on the current young generation. Equation (1.32) is thus strictly positive for quasi-linear preferences or a sufficiently weak income effect, implying $\theta^*_t > \theta^{eq}_t$.

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[19] To see this, refer to the Appendix.

[20] This is due to the right-skewed income distribution. Note that average consumption $\bar{d}(\theta_t)$ is given by $D(\theta_t)/(2+n)$.

Now, assume $\tilde{y}_t \leq y_{M,t}$ implying $\alpha_t^{eq} = 1$. The ecotax rate in the political equilibrium is then implicitly given by:

$$-d_M^Y(\theta_t) + D(\theta_t)(1-\varepsilon_{D,\theta})\frac{y_{M,t}}{(1+n)(1-\eta)\bar{y}_t} - [1+\rho(1-\delta)]\frac{\phi D'(\theta_t)}{c(q_t)} = 0 \; . \quad (1.33)$$

Again, we evaluate the social planner's first-order condition with respect to θ_t at this equation:

$$\left.\frac{\partial \mathcal{W}(\theta_t, \alpha_t = 1)}{\partial \theta_t}\right|_{\theta_t^{eq}, \alpha_t^{eq}=1} \gtreqless 0 \Leftrightarrow d_M^Y(\theta_t) - \bar{d}(\theta_t)\left[1 - \frac{1-\varepsilon_{D,\theta}}{1-\eta}\left(1 - \frac{2+n}{1+n}\frac{y_{M,t}}{\bar{y}_t}\right)\right]$$
$$- \frac{1}{1+n}\frac{\phi D'(\theta_t)}{c(q_t)}\frac{z(z+n)}{1-z} \gtreqless 0 \; . \quad (1.34)$$

The sign of the above equation is indeterminate, and the median voter's preferred green tax rate may well be close to or even *above* the tax rate chosen by the social planner. We name the term in the first line *'political economy effect'* and the one in the second line *'environmental sustainability effect'*. Unless $\delta = 1$, the latter effect is always strictly positive as the social planner internalizes more of the environmental damage accruing in the future while the first effect is ambiguous in sign. The political economy effect may thus drag the tax rate chosen in the political equilibrium above the optimal tax rate. To illustrate this, assume for a moment that $\delta = 1$, implying that emissions do not accumulate in the atmosphere and the second line drops out. Using equation (1.19), we have:

$$\theta_t^* \gtreqless \theta_t^{eq} \quad \Leftrightarrow \quad \frac{1-\varepsilon_{D,\theta}}{1-\eta}\left(1 - \frac{2+n}{1+n}\frac{y_{M,t}}{\bar{y}_t}\right) \gtreqless 1 - \frac{d_M^Y(\theta_t)}{\bar{d}(\theta_t)} \; . \quad (1.35)$$

Importantly, the lower $d_M^Y(\theta_t)$ is compared to $\bar{d}(\theta_t)$, the more likely it is that the politically determined tax rate lies above the socially optimal one. For quasi-linear preferences, $d_M^Y(\theta_t) = \bar{d}(\theta_t)$, we get:

$$\theta_t^* \gtreqless \theta_t^{eq} \quad \Leftrightarrow \quad 1 \gtreqless \frac{2+n}{1+n}\frac{y_{M,t}}{\bar{y}_t} \quad \Leftrightarrow \quad y_{M,t} \lesseqgtr \frac{\tilde{y}_t}{1-\eta} \; . \quad (1.36)$$

In this case, the median voter's environmental tax rate lies above the adjusted Pigouvian tax rate whenever his income exceeds the critical income $\tilde{y}_t$ by the factor $1/(1-\eta)$.

The reasoning behind this result can best be understood by comparing the social planner's and median voter's first-order conditions with respect to θ_t. For $\delta = 1$

and $\alpha_t = 1$, equations (1.16) and (1.23) reduce to:

$$\frac{D(\theta_t)(1-\varepsilon_{D,\theta})}{1-\eta} \quad -\frac{\phi D'(\theta_t)}{c(q_t)}(2+n) \quad -\bar{d}(\theta_t)(2+n) = 0 \ , \tag{1.37}$$

$$\frac{D(\theta_t)(1-\varepsilon_{D,\theta})}{1-\eta}\frac{1}{1+n}\frac{y_{M,t}}{\bar{y}_t} \quad -\frac{\phi D'(\theta_t)}{c(q_t)} \quad -d_M^Y(\theta_t) = 0 \ . \tag{1.38}$$

The first two terms in each equation represent the marginal benefits of a tax increase due to revenue recycling through the pension system and due to the reduction of environmental damages. The last terms illustrate the marginal costs of higher ecotaxes. First, suppose there are no income effects, i.e. $\bar{d}(\theta_t) = d_M^Y(\theta_t)$. As the median voter does not take into account that all other individuals are also affected by changes in the green tax rate, he underestimates *both* benefits and costs compared to the social planner.[21] While the underestimation of marginal costs raises the tax rate in the political equilibrium, the underestimation of marginal benefits lowers the tax rate. A graphical illustration is given in the Appendix. Higher income of the median voter (compared to average income) thereby makes the latter effect less severe as can be seen from the first term in the second line. Note that only the combined underestimation of benefits and costs makes the overall effect ambiguous in sign. In other words, although the median voter tends to vote for a higher green tax rate because he does not consider that the costs of higher taxes are borne by all, an inefficiently high tax rate can only prevail in the political equilibrium if marginal benefits are not underestimated too much by the median voter. This happens whenever the median voter's income is sufficiently high compared to average income. The presence of income effects increases the underestimation of individual marginal costs (compared to overall marginal costs) and a higher than socially optimal green tax rate is more likely to emerge.

For $\delta < 1$, the median voter still desires an inefficiently high tax rate according to equation (1.34) if his income is high enough (compared to average income) so as to outweigh the environmental sustainability effect. The following Proposition summarizes our results for the outcome of the political process.

Proposition 1.1 (Political equilibrium as compared to social optimum)
The equilibrium share of taxes devoted to the pension scheme, α_t^{eq}, is

$$\alpha_t^{eq} = 0 \quad \textit{for} \quad y_{M,t}^{\alpha} < \tilde{y}_t \ ,$$
$$\alpha_t^{eq} = 1 \quad \textit{for} \quad y_{M,t}^{\alpha} \geq \tilde{y}_t \ .$$

[21] Note that $y_{M,t}^Y < (1+n)\bar{y}_t$ for right-skewed income distributions.

For $n > 0$, we can always identify a young individual who is the median voter. His preferred tax rate may be lower or higher than (or equal to) the socially optimal tax rate. Specifically,

(i) *for no stock pollution, $\delta = 1$, we find*

$$\theta_t^{eq} \gtreqless \theta_t^* \qquad for \qquad \frac{1-\varepsilon_{D,\theta}}{1-\eta}\left(1-(1-\eta)\frac{y_{M,t}}{\tilde{y}_t}\right) \lesseqgtr 1-\frac{d_M^Y(\theta_t)}{\bar{d}(\theta_t)} \ ,$$

which for quasi-linear preferences, $d_M^Y(\theta_t) = \bar{d}(\theta_t)$, reduces to

$$\theta_t^{eq} \gtreqless \theta_t^* \qquad for \qquad y_{M,t} \gtreqless \tilde{y}_t/(1-\eta) \ .$$

(ii) *For $\delta < 1$, the equilibrium tax rate exceeds the first-best tax rate if the political economy effect is negative and outweighs the environmental sustainability effect, i.e. equation (1.34) is negative.*

Our results are driven by demography, income distribution, the tax-price elasticity of the polluting good as well as the parameters ρ, δ and η.[22] Whether we can observe an inefficiently high or low tax rate in reality is thus an empirical question which we address in Section 1.6.

1.5 Demographic change

Demography plays an important role in our model. Not only does demography directly affect the political equilibrium by determining the median voter, it also indirectly affects the political outcome by changing individuals' preferences. In this section, we analyze the impact of a changing n on the desired tax rates of the median voter and the social planner. As Germany is confronted with a dramatic population aging, we concentrate on the effects of a decreasing but still positive n as also projected by the OECD for Germany. The analysis is more complex than one could have anticipated. So, we concentrate here on quasi-linear preferences and, at the end of this section, provide some intuition how income effects influence our results.

Applying the implicit function theorem to equations (1.17), (1.23) and (1.25), we can establish the following Lemma.

[22] Importantly, whether the tax rate in the political equilibrium is inefficiently low or high does not depend on the size of marginal damages, ϕ. Solving equations (1.17) for θ_t^* and (1.31) or (1.33) for θ_t^M and subtracting one from the other, ϕ can be factored out. The marginal social damage has only a level effect on the tax rates.

Lemma 1.4 (Tax rates and demographic change)
With no income effects, the following conditions hold for the desired tax rates of young and old individuals and the social planner:

$$\frac{\partial\theta_t^*}{\partial n} = \frac{\phi D'(\theta_t)[1+\rho(1-\delta)]/(1-z)^2}{SOC_\theta^*} > 0 \ , \tag{1.39}$$

$$\frac{\partial\theta_{i,t}^Y}{\partial n} = \frac{\phi d'(\theta_t)[1+\rho(1-\delta)] + \dfrac{\alpha_t c(q_t) d(\theta_t)(1-\varepsilon_{D,\theta}) y_{i,t}}{(1+n)^2(1-\eta)\bar{y}_t}}{SOC_\theta^Y} \gtreqless 0 \ , \tag{1.40}$$

$$\frac{\partial\theta_{i,t}^O}{\partial n} = \frac{\phi d'(\theta_t)}{SOC_\theta^O} > 0 \ . \tag{1.41}$$

Obviously, a lower population growth rate decreases the optimal ecotax, as less environmental damage needs to be internalized. A similar reasoning applies to the old's and young's preferred tax rates. With a lower n, both desire a lower ecotax because of lower overall pollution. If, however, at least some tax revenue is used to cut pension contributions, i.e. $\alpha_t > 0$, a second effect shows up in equation (1.40) which makes a young type-i's reaction to a decrease in n ambiguous in sign. To see the intuition behind this effect, we differentiate equation (1.9) with respect to n: $\partial^2 b(\theta_t, \alpha_t)/\partial\theta_t\partial n > 0$. That is, for given pension benefits, a lower n makes tax increases more effective in reducing pension contributions and increases the attractiveness of higher ecotaxes.[23] Hence for $\alpha_t > 0$, depending on the relative strength of the effects at work, the young's preferred ecotax rate may rise or fall in response to a change in n, as indicated by the diagonal arrows in Figure 1.2.

Having characterized how the different generations react to a change in n with respect to their desired tax rate, we also need to take into account that the decisive voter changes when n marginally changes. Suppose that $\alpha_t^{eq} = 0$ at the beginning. If n decreases, we obtain by Lemma 1.4 that the politically induced tax rate decreases as well, given that the median voter's income remains unchanged. However, a decrease in the population growth rate also increases the share of the old. Hence, the median voter shifts to a young agent of lower income.[24] This median voter effect has – for

[23] To keep the pension scheme solvent over the long term, the so-called demographic 'sustainability factor' was introduced in 2005. In determining pension benefits, the German pension formula now takes into account the number of pensioners relative to the number of contributors. Specifically, population aging not only affects the young in that it increases pension contributions, but also reduces pension benefits of the current old. Introducing the demographic sustainability factor in our analysis would thereby reduce the attractiveness of higher ecotaxes due to population aging for the young in society.

[24] Note that we assume that the income distribution is not affected by a marginal change in n.

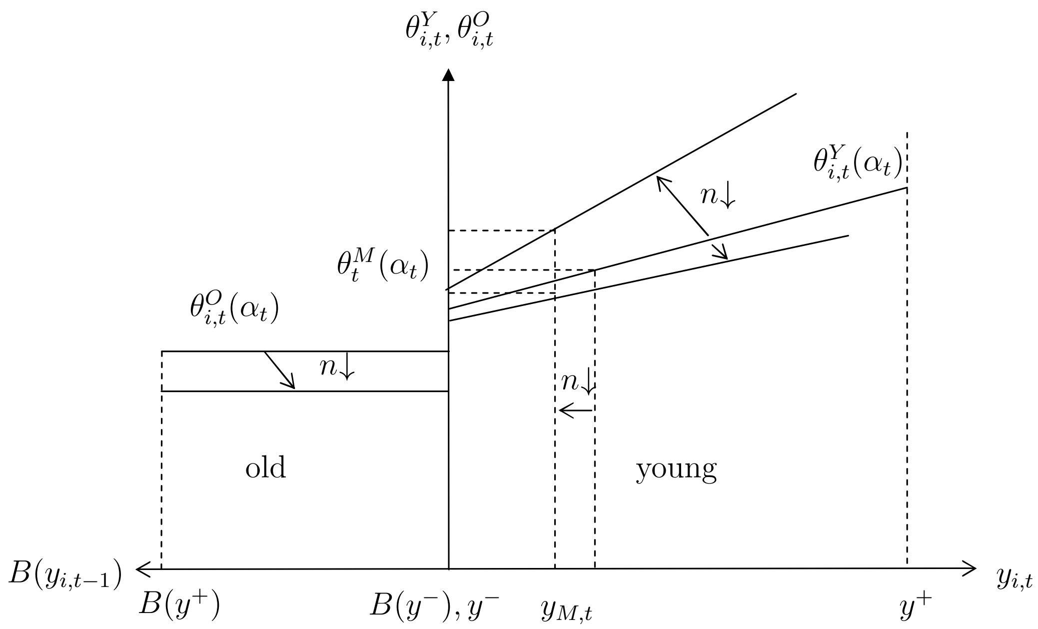

Figure 1.2: Demographic change for $c'(q_t) = 0$ and $\alpha_t > 0$.

quasi-linear preferences – no impact since for $\alpha_t^{eq} = 0$ all young agents prefer the same tax rate (see equation (1.24)). If the initial equilibrium is given by $\alpha_t^{eq} = 1$, Lemma 1.4 predicts an ambiguous effect of the median voter's desired tax rate to a change in n, given that his income stays the same. But, again, the median voter changes to an individual with lower income (indicated by the horizontal arrow in Figure 1.2) who for $\alpha_t^{eq} = 1$ prefers a lower ecotax rate. In sum, the equilibrium tax rate may either rise or fall.[25]

In addition to the effects described above, we need to think of how possible income effects change the political outcome in an aging society. Assuming that the income distribution remains the same and pension benefits remain constant, the now lower mass of young individuals needs to pay higher pension contributions. This, along with the in any case lower sum of incomes in the economy, leads to lower consumption of the polluting good. As a consequence the new median voter now consumes less, that is, $d_M^Y(\theta_t)$ falls, and he desires a higher tax rate than before. As $\bar{d}(\theta_t)$ also falls, we cannot say whether the wedge between the socially optimal and the politically determined tax rate becomes larger or smaller (see the first two addends in equations (1.32) and (1.34)).

Whether and how demographic change, as expected for Germany, shifts the political equilibrium will be explored in the following section.

[25] Additionally, the threshold income $\tilde{y}_t$ becomes smaller as $\partial\tilde{y}_t/\partial n = (1-\eta)\bar{y}_t/(2+n)^2 > 0$ and the median voter with respect to the budgetary rule also shifts to an individual with lower income. Thus population aging has an ambiguous effect on the choice of α_t^{eq}.

1.6 A calibration of the model

In this section, we calibrate our model to the German economy, focusing on the ecotax on gasoline, as transport-related expenses represent the largest share of households' energy expenditure. We inspect whether the refund rule observed in reality can be predicted by our model and make some tentative statements on whether the German ecotax rate exceeds or falls short of the adjusted Pigouvian tax. To this end, we calibrate the model parameters (reasonable estimates of which are found in the literature) such that the tax rate in the political equilibrium matches the actual German ecotax, and then determine the social optimum. Computations are undertaken for the year 2008 (for reasons of data availability) and for a pensioner/contributor ratio that is projected for the year 2028. Household data on a monthly basis for the distribution of gross labor income, for disposable incomes and motor fuel expenditure are taken from the EVS (Sample Survey of Income and Expenditure) from the Federal Statistical Office in Germany. Data on population size are obtained from the OECD database.

To compute n, we divide the number of retired individuals above the age of 65 (which is 16,624,000 people), by the number of working individuals between the age of 20 and 64 (49,715,000 people). Consequently, the pensioner/contributor ratio is $1/(1+n)$=0.33 and n equals 1.99. For the year 2008, the Federal Statistical Office reports an average gasoline price of €1.40 per liter. Deducting the ecotax of €0.15, we get a producer price of €1.25 that includes all pre-reform taxes. Normalizing the producer price to unity yields 0.8 liters, which are equivalent to 0.00184 tonnes of CO_2.[26] The ecotax per 0.8 liters then amounts to θ^{eq}_{2008}=€0.12.

We estimate equation (1.6) on the basis of our data, using disposable incomes and expenditure on transport fuels of all households:

$$d^j_i(\theta_{2008}) = 22.164 + 0.0254 I^j_{i,2008} \ . \tag{1.42}$$

Following Cremer et al. (2007, 2008) that $c(q_t) \equiv 1 - \beta q_t = 1 - \beta(1 + 0.12)$, we have with the above equation: $-c'(q_{2008})/c(q_{2008}) = \beta/(1 - 1.12\beta) = 0.0254$. Solving for β and inserting back yields $c(q_{2008}) = 0.9723$. Furthermore, average income and average expenditure on transport-related fuels over all households are $\bar{y}_{2008}$=€2056 and $\bar{d}(\theta_{2008})$=€98.

Kleven and Kreiner (2003) estimate the marginal costs of public funds for Germany and report a lower bound of 1.55 for a proportional tax reform. For our modelling

[26] The conversion factor from liters to tonnes of CO_2 can be found in footnote 4.

framework, this implies an η of 0.37.[27]

The critical income below which the young want all ecotax revenue to be given back in a lump-sum fashion is: $\tilde{y}_{2008} = (1+1.99)/(2+1.99)(1-0.37)$€2056=€971 (see equation (1.19)). By equation (1.22), we have $F(y_{M,2008})$=0.33 which yields $y_{M,2008}$=€1091 so that it is indeed optimal for the median voter to vote for earmarking the ecotax revenue as reductions in pension contributions.

The parameter values $\varepsilon_{D,\theta}$, δ and ρ are based on estimates in the literature. As a starting point for the demand elasticity, we take the average long-run price elasticity for gasoline from Espey (1996), $\varepsilon_{D,\theta} = 0.58$. To provide some sensitivity analysis, we report our results for $\varepsilon_{D,\theta} = 0.58 \pm 0.15$.[28] It is a more difficult endeavor to find estimates for the uptake of anthropogenic CO_2 by biological and abiological sinks, let alone to squeeze them into a single parameter.[29] The uptake capacity is reservoir-specific and depends on the state of the system, i.e., on the initial level and the additional flux of CO_2 released into the atmosphere, and hence varies over time. Nevertheless, the IPCC (2007) states in the "Executive Summary" of Chapter 7 on the carbon cycle: "About half of a CO_2 pulse to the atmosphere is removed over a timescale of 30 years; a further 30% is removed within a few centuries; and the remaining 20% will typically stay in the atmosphere for many thousands of years." As one period in our model corresponds to 45 years, we take the IPCC's estimate as a lower bound and vary δ from 0.5 to 1. Finally, we are restricted by the condition $\rho(1+n) < 1$, that is, $\rho < 0.33$ for the n we employ. Using a discount rate of 3% per year as in Nordhaus and Boyer (2000), we find $\rho = 0.264 < 0.33$.[30]

In order to determine the median voter over the tax rate, we need to check on the basis of our data whether the young's ecotax rate is increasing or decreasing in gross labor income, equation (1.24). Within the range of our parameter estimates from above, this equation is always strictly positive for $\alpha^{eq}_{2008} = 1$. By the first part of Lemma 1.3, the median voter is identical to the one with respect to the budgetary rule.[31]

[27] Since pension benefits in Germany are to a large extent earnings-related, the deadweight loss associated with the pension system is known to be smaller than for general income taxes. Thus, we see the lowest estimate of their analysis as an appropriate value for the calibration of our model.

[28] Note that we require $\eta < \varepsilon_{D,\theta}$ from our theoretical model.

[29] The long term abiological sinks are dissolution in the oceans and chemical neutralization by reaction with carbonates and basic igneous rocks, see Archer et al. (1997).

[30] Nordhaus (2007) argues that information on intertemporal preferences can be inferred from observations of investment decisions on capital markets and, therefore, a positive discount rate can be employed. Note that in our model, the discount rate is equal to the rate of pure time preference since the growth rate of per capita GDP is equal to zero.

[31] As indicated by footnote 18, agents with incomes above the MDB actually prefer lower ecotaxes

$\varepsilon_{D,\theta}$		0.43	0.58	0.73
δ:	0.5	€0.04	€0.01	€0.00
	0.6	€0.05	€0.02	€0.01
	0.7	€0.05	€0.03	€0.02
	0.8	€0.06	€0.03	€0.03
	0.9	€0.06	€0.04	€0.04
	1.0	€0.07	€0.04	€0.04

Table 1.1: $\theta_t^{eq} - \theta_t^*$ for the year 2008.

As estimates for the marginal social damage from CO_2 emissions vary enormously, we infer for different values of δ and $\varepsilon_{D,\theta}$ the corresponding ϕ's so as to match the politically determined tax rate to the actual German ecotax. Converting these values into € per tonne of CO_2, we find that they are within the range of €1.26 to €8.28. For the given θ_{2008}^{eq}, they are the higher the more CO_2 is removed from the atmosphere and the higher the price elasticity of demand. Not surprisingly, we find a low social marginal damage for all parameter constellations. This is because a tax of approximately €0.50 per liter had been levied on mineral oil prior to the ecotax reform. The total tax on gasoline (excluding the VAT which comes on top) hence amounts to €0.65 (equals €285 per tonne of CO_2). The pre-reform tax on gasoline had already internalized a huge part of the external effect.

We are now able to calculate θ_{2008}^* according to equation (1.17). Table 1.1 shows the difference between the politically determined and Pigouvian tax rate, $\theta_{2008}^{eq} - \theta_{2008}^*$, for different parameter constellations.

Our simulations illustrate that the tax rate chosen by the median voter is at least as high as the socially optimal tax for all parameter constellations considered. The difference rises with δ since a higher CO_2 uptake rate (less CO_2 remains in the atmosphere) causes the social planner to internalize less damage accruing in the future which the median voter does anyway not take into account. However, the redistributive motive of the median voter under the equilibrium budgetary rule prevails and drags the desired tax rate even more above the socially optimal one. In addition, the spread between the two tax rates rises the more inelastic the price elasticity of demand. The intuition is that the more inelastic demand is, the less consumers can evade the tax burden. The

than predicted by our model. However, the ordering of preferred ecotaxes and thus the determination of the median voter are unaffected. This is because we use disposable incomes which already include this peculiarity of the German pension scheme.

social planner takes this into account and chooses a lower tax rate in order not to strain the currently living generations too much. So, for lower elasticities, the fiscal effects of redistributing ecotax revenue through the pension system dominate. Depending on the underlying parameter constellations, the politically determined tax rate may exceed the adjusted Pigouvian one by up to €0.07, i.e., by more than 100%.[32]

To illustrate numerically the role of demographic change in our model, assume that n decreases from 1.99 to 1, or equivalently the pensioner/contributor ratio worsens from 0.33 to 0.5, as projected by the OECD for the year 2028 approximately. As we cannot reasonably speculate about technologies and income distributions in 2028, we keep everything else constant at 2008 levels. The first effect of this change in n is that now the median voter prefers an eco-bonus to the alternative cut in pension contributions since $\tilde{y}_{2028}$=€864 and $F(y_{M,2028}) = 0.25$, implying $y_{M,2028}$=€769. This makes an inefficiently high tax rate in the political equilibrium less likely. For simplicity, we focus on $\delta = 0.5$ and $\varepsilon_{D,\theta} = 0.58$, corresponding to ϕ=€0.0094 per 0.8 liters or €5.11 per tonne of CO_2. The Pigouvian tax rate then amounts to €0.07 which is lower than previously (see Table 1.1). Since $\alpha^{eq}_{2028} = 0$, equation (1.24) is negative. We order young and old individuals according to their desired tax rates. This yields a tax rate in the political equilibrium of €0.04 which now falls short of the social optimum. It is only one third of the German tax rate after the 1998-2003 reform.[33]

1.7 Discussion

The previous sections have shown that inefficiently high or close to efficient tax rates are more likely to prevail under majority voting if some share of tax revenue is devoted to the pension scheme. As Proposition 1.1 states, this is more likely the more income the median voter has at his disposal. The second instrument, the budgetary rule, opens the possibility to 'buy' political support for a higher ecotax from young voters. This possibility is limited if all generations benefit alike from the refund rule. In Cremer et al. (2004), the constitutional planner is able to implement the efficient tax rate in the voting stage by choosing an appropriate refund rule in the first stage which is not subject to voting.[34] Our positive analysis of both instruments suggests that the refund

[32] Note that to get tax rates per liter, we need to divide all numbers in Table 1.1 by 0.8.

[33] Also all other parameter constellations in Table 1.1 lead to inefficiently low tax rates in the political equilibrium.

[34] If we allowed a constitutional planner to set the refund rule in the first stage, taking into account the distortions from voting over the tax rate in the second stage, he would equate θ^*_t with θ^{eq}_t and

rule is – under certain conditions – able to reduce the overall distortion in the economy. Along these lines, the double dividend argument has politico-economic implications because it may go along with more support for higher ecotaxes.[35] A similar argument is given by Aidt (2010) who finds in a probabilistic voting model with lobbying that the endogenous choice of the refund rule may render higher ecotax rates politically more acceptable.

The key to our results is the redistribution of ecotax revenue to young voters who are – for positive population growth – decisive in the political process. They support higher ecotaxes, *inter alia*, because they benefit from reductions in pension contributions, but they would similarly gain from reductions in personal income or other social security taxes which are levied proportionally or overproportionally to income. Such policies favor young working individuals – the more so the more progressive these systems are – while the old generation is largely unaffected. As already mentioned in the introduction, ecotax reforms of this kind were carried out in Sweden, Denmark, the Netherlands and the UK. In our theoretical model, the pension contribution rate can more generally be interpreted as a personal income tax rate, and instead of holding pension benefits constant, total government spending could be kept fixed. An increase in the ecotax then again proves more advantageous for young individuals, in particular high-income earners, than for retirees if not all ecotax revenue is distributed back lump-sum. Therefore, our model can well be applied – with only minor modifications – to other European countries and provides some evidence that distributing revenue generated by environmental regulation to young agents is a strategy to secure political support for higher ecotaxes.[36]

Since generations are dynastically linked and since today's consumption of the dirty good also affects the offspring of each generation alive today, that is, its children, children's children and so on, a more adequate representation of preferences may be to incorporate intergenerational altruism (see, e.g., Barro, 1974). Then, today's old would not only derive utility from their own consumption but also from all future generations' utility levels. Assuming that the income-type is passed on to the next generation, how would such intergenerational altruism change the political equilibrium? First, note

solve for α_t. As can be easily verified, whether efficiency can be achieved depends on the income distribution and the parameter values ρ, δ, n, η. Note that α_t must lie in the interval $[0; 1]$.

[35] Empirical and experimental studies examining public support for taxation have mainly focused on transport-related taxes, see, *e.g.*, Schuitema and Steg (2008), or Sælen and Kallbekken (2011). For a study on tax aversion and revenue recycling in the lab see Kallbekken et al. (2011).

[36] Comparably high tax rates on mineral oil in the afore-mentioned countries can be seen as indication of this hypothesis, see the OECD/EEA database on instruments used for environmental policy and natural resources management.

that the indirect utility of the old then also depends on the income of the young. Their preferred green tax rate may then still fall (under lump-sum redistribution) or rise (under redistribution through the pension scheme) in their children's income. High-income families may thus for $\alpha_t^{eq} = 1$ vote for higher green taxes as compared to low-income families. They may also prefer earmarking of ecotax revenue to the pension scheme instead of lump-sum transfers. But, more importantly, the current old and young generations internalize the externality of their dirty good consumption on all future generations. This increases the preferred green tax rate of both generations and thus also of the median voter. Nevertheless, the *intra*generational externality remains and if altruism is only one-sided, the young do not internalize the impact of their dirty good consumption on their parents' utility. In other words, the political equilibrium is probably still different from the social optimum, but compared to no altruism it yields a higher green tax rate and, for given parameter constellations, it becomes more likely that ecotax revenue is earmarked to the pension scheme.[37]

Our theoretical model comprises two periods for each generation, implying that all young agents are of the same age. In reality, however, a young individual approaching pension age may anticipate the effects of his vote on his welfare in old age and therefore vote differently compared to a young agent who has just entered working life, particularly if the next elections do not come up soon. Sinn and Übelmesser (2003) find that, in Germany, the median voter is approximately of age 48 around 2009 and of age 53 around 2030. Breaking down the lifetime of each generation in our model by introducing different age cohorts, this aging of the median voter would reduce the attractiveness of higher green taxes in the political equilibrium.

A simplifying assumption in many regards is the linear damage function in our model. It renders the problem analytically tractable in the first place, because it separates the decisions on the tax rates in different periods. Therefore, no expectations with respect to future tax rates have to be made. Although previous related studies assume convex damage costs, they solely concentrate on one period and thus do not take account of the accumulation of emissions in the atmosphere. In our model, constant marginal damages are the only viable solution in the calibration, as otherwise we would have to project the future emissions path. To our knowledge, no country-specific estimate of the damage function is available. Yet, it is widely believed that this function is convex. Not incorporating this feature leads to an underestimation of the adjusted Pigouvian

[37] To avoid double-counting, the altruistic component should not enter the welfare function which implies that the social optimum remains unaffected by altruistic preferences (see, e.g., Hammond, 1987).

tax rate, as the social planner would take into account that the damage from emissions today would rise in the future with higher levels of CO_2 in the atmosphere. He would then want to lower emissions today via a higher tax rate. By contrast, the median voter's chosen tax rate would not differ significantly. He only observes two points on the damage function – today and in his old age. In this case, a linear specification that connects these two points is a good enough approximation.

1.8 Concluding remarks

We have analyzed the political determination of the German ecotax package theoretically and numerically. In the OLG model we employ, voters have different preferences with respect to the ecotax reform due to income and, more importantly, due to age. We found that old individuals are more likely to prefer lower tax rates than young individuals with the same income, as they do not benefit from a reduction in pension contributions and do not suffer from environmental damage in the future. Furthermore, both old individuals and young low-income earners vote for full lump-sum redistribution of tax revenue. High-income earners, however, benefit more from a reduction of pension contributions than from lump-sum transfers, because consumption of the externality-generating good rises less than proportionally with income while pension contributions are proportional to income.

For a positive population growth, the median voter over both dimensions was found to be of the young generation. The environmental tax rate in the political equilibrium can be higher or lower than the efficient tax rate (or incidentally coincide with it), depending mainly on demography and income distribution. Whereas the social planner would choose a share of tax revenue devoted to the pension scheme equal to unity so as to reduce the deadweight loss from pension contributions, this share was shown to be either zero or unity in the political equilibrium.

The calibration of the model gave a taste of the situation in Germany. First, it is indeed optimal for the median voter to choose a reduction of pension contributions rather than a lump-sum transfer. Second, for reasonable parameter values, the German ecotax lies above its optimal level, the more so the more CO_2 is degraded and removed in the atmosphere within the lifetime of one generation, and the more inelastic the demand of the dirty good. Further demographic change in Germany towards a 'gerontocracy' lowers the politically induced tax rate below its optimal level because the median voter no longer disposes of sufficiently high income in the future.

1.9 Appendix

Derivation of Social Optimum

We can rewrite equation (1.14) by splitting up the last term into the utility of the currently young and the sum of utilities of all future (young) generations:

$$\begin{aligned}\mathcal{W}_t(\theta_t, \alpha_t) = &\int_{y^-}^{y^+} V_{i,t}^O(\theta_t, \alpha_t)\mathrm{d}F(y_{t-1}) \\ &+ (1+n)\left[\int_{y^-}^{y^+} V_{i,t}^Y(\theta_t, \alpha_t)\mathrm{d}F(y_t) + \sum_{x=t+1}^{\infty}\Big((1+n)\rho\Big)^{x-t}\int_{y^-}^{y^+} V_{i,x}^Y(\theta_t)\mathrm{d}F(y_x)\right] ,\end{aligned}$$

where the utilities of all future generations do not depend on α_t. This implies that for these generations only marginal damages from emissions remain in the first-order condition below. Taking the derivative with respect to the tax rate, we then have:

$$\begin{aligned}\frac{\partial \mathcal{W}_t(.)}{\partial \theta_t} &= (2+n)a'(q_t) + c'(q_t)\left(\bar{I}_t^O + (1+n)\bar{I}_t^Y\right) + c(q_t)D(\theta_t)(1-\varepsilon_{D,\theta})\frac{1-\eta(1-\alpha_t)}{1-\eta} \\ &- (2+n)\phi D'(\theta_t) - z\phi D'(\theta_t) - (1+n)[1+\rho(1-\delta)]\phi D'(\theta_t)\sum_{x=t+1}^{\infty} z^{x-t} = 0 ,\end{aligned}$$

where $\bar{I}_t^O = \bar{B}_t + \tau_t$ and $\bar{I}_t^Y = (1-b_t)\bar{y}_t + (1+n)\tau_t$. Dividing by $c(q_t)$, using equation (1.6), carrying out an index transformation and assuming that $\rho(1+n) < 1$ as $\sum_{t=0}^{\infty}[\rho(1+n)]^t = 1/[1-\rho(1+n)]$ only converges for the argument being less than unity, yields equation (1.16) in the text.

The second-order condition with respect to the tax rate is as follows:

$$\begin{aligned}SOC_\theta^* =&(2+n)a''(q_t) + c''(q_t)\left(\bar{I}_t^O + (1+n)\bar{I}_t^Y\right) + 2c'(q_t)D(\theta_t)(1-\varepsilon_{D,\theta})A \\ &+ 2c(q_t)D'(\theta_t)A + \left(c(q_t)\theta_t A - \frac{2+n}{1-z}\phi\right)D''(\theta_t) , \qquad (1.A.1)\end{aligned}$$

where $A \equiv \dfrac{1-\eta(1-\alpha_t)}{1-\eta} > 0$.

Single-Peakedness

The second-order conditions of equations (1.23) and (1.25) are given by

$$\begin{aligned}SOC_\theta^Y =&a''(q_t) + c''(q_t)I_{i,t}^Y + 2c'(q_t)D(\theta_t)(1-\varepsilon_{D,\theta})\Omega + 2c(q_t)D'(\theta_t)\Omega \qquad (1.A.2) \\ &+ (c(q_t)\theta_t\Omega - [1+\rho(1-\delta)]\phi)D''(\theta_t) ,\end{aligned}$$

$$SOC_\theta^O = a''(q_t) + c''(q_t) I_{i,t}^O + 2c'(q_t)\frac{1-\alpha_t}{2+n} D(\theta_t)(1-\varepsilon_{D,\theta}) + 2c(q_t)D'(\theta_t)\frac{1-\alpha_t}{2+n} + \left(c(q_t)\theta_t \frac{1-\alpha_t}{2+n} - \phi\right) D''(\theta_t) \ , \quad (1.A.3)$$

where $\Omega \equiv \frac{\alpha_t y_{i,t}}{(1+n)(1-\eta)\bar{y}_t} + \frac{1-\alpha_t}{2+n} > 0$.

Illustration of Lemma 1.3

Even if $\partial\theta_{i,t}^Y/\partial y_{i,t} < 0$, there is only one young median voter in the following two cases. The dashed ellipses in Figure 1.3 illustrate a mass of young individuals that exceeds $(2+n)/2$. In Figure 1.3(a), the median voter is then determined by $F(y^-)+(1+n)F(y_{M,t}) = (2+n)/2$ with $F(y^-) = 0$ whereas he is determined by $F(y^+)+(1+n)F(y_{M,t}) = (2+n)/2$ with $F(y^+) = 1$ in Figure 1.3(b).

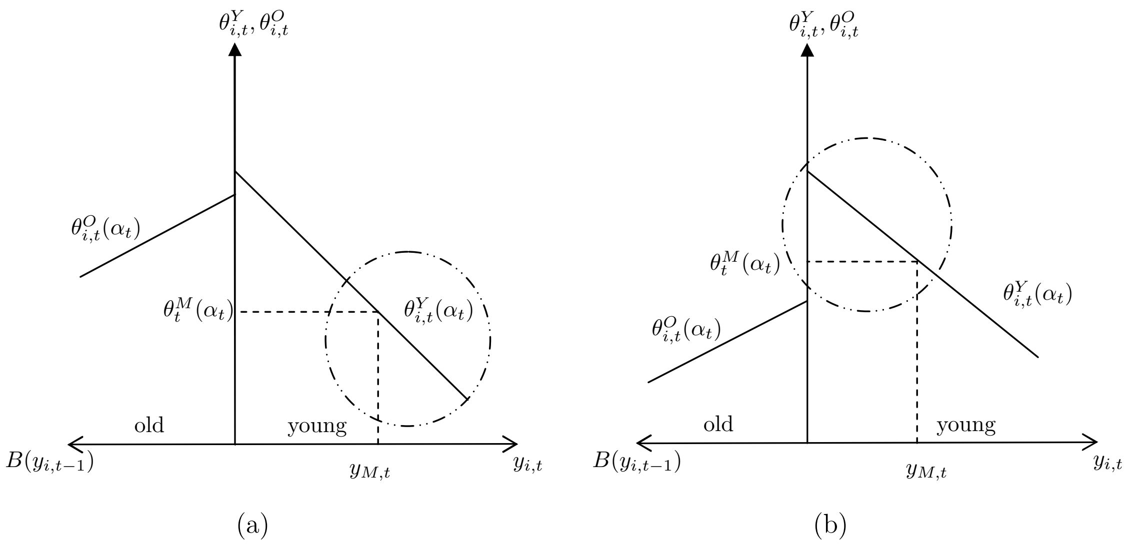

Figure 1.3: Determination of the median voter.

Comparison of θ_t^* and θ_t^{eq} for $y_{M,t}^\alpha \geq \tilde{y}_t$

Consider equations (1.37) and (1.38). Compared to the social planner, the median voter underestimates both the marginal costs (MC) and the marginal benefits (MB) of higher ecotaxes. Figure 1.4 illustrates. Specifically, the MC and MB for the social planner (indicated by a superscript *) and the median voter (superscript ^{M}) are given by:

$$\begin{aligned}
\text{MC}^* &\equiv (2+n)\bar{d}(\theta_t) > d_M^Y(\theta_t) \equiv \text{MC}^M \ , \\
\text{MB}^* &\equiv \frac{D(\theta_t)(1-\varepsilon_{D,\theta})}{1-\eta} - (2+n)\frac{\phi D'(\theta_t)}{c(q_t)} \geq \\
&\quad \frac{D(\theta_t)(1-\varepsilon_{D,\theta})}{1-\eta}\frac{y_{M,t}}{\bar{y}_t}\frac{1}{1+n} - \frac{\phi D'(\theta_t)}{c(q_t)} \equiv \text{MB}^M \ .
\end{aligned}$$

Both MC and MB decrease in θ_t and, additionally, $\left|\frac{\partial MC}{\partial \theta_t}\right| < \left|\frac{\partial MB}{\partial \theta_t}\right|$ by the SOCs (equations (1.A.1) and (1.A.3)). That is, the (negative) slope of marginal benefits is steeper than for marginal costs which ensures a maximum.

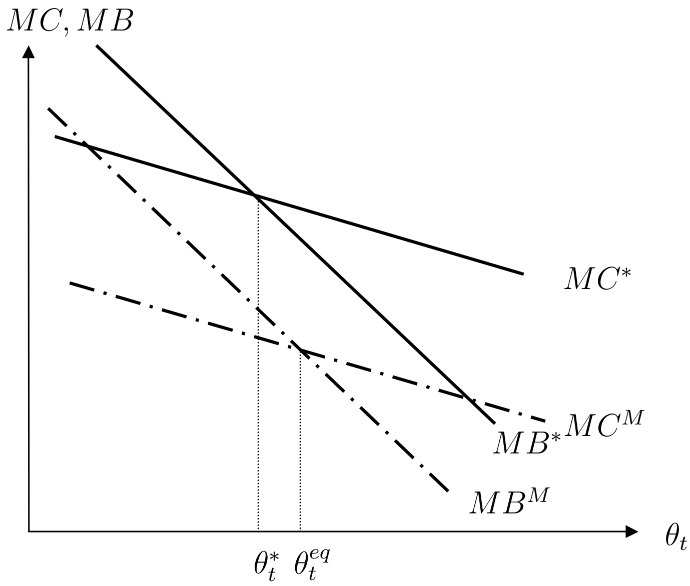

Figure 1.4: Comparison of θ_t^{eq} and θ_t^* for $\alpha_t^{eq} = 1$.

Chapter 2

Political Influence on Non-cooperative International Climate Policy

2.1 Introduction

When analyzing international (environmental) policy, we often consider individual countries to be represented by a single benevolent decision maker, e.g. a government, acting in the best interest of the country as a whole. In this paper, we depart from this idealized abstraction by assuming that each country's decision maker is vulnerable to the influence of national political competition. As a consequence, international policy is governed by two forces: (i) the influence of political competition on a national level and (ii) the interplay of national governments on the international policy arena.

By political competition we mean that incumbent politicians not only maximize the welfare of the general electorate (national social welfare) but are also susceptible to the influence of lobby groups which try to sway them in their favor by providing campaign contributions, information or simply bribes. This may give them an advantage over their challengers at the next election and hence increases their likelihood of reelection. Deviating from the socially optimal policy, however, leads to an alienation of voters and decreases this likelihood. Policy-makers thus face a trade-off between securing political support by interest groups and maximizing national social welfare.

On the international level, the particular environmental policy we consider is the non-cooperative formation of an international emission permit market (Helm, 2003). Our choice for non-cooperative climate policies is twofold. On the one hand, the international negotiations for a successor of the Kyoto Protocol in Durban in 2012 have shown how difficult it is to achieve international cooperation. As a consequence, alternatives such as linking already established regional emissions trading systems have been discussed (Flachsland et al., 2009).[1] On the other hand, Carbone et al. (2009) have recently shown that even non-cooperative climate policies exhibit substantial potential for greenhouse gas reductions.

We analyze the political economy of international climate policy in a two-country setup with legislative lobbying in each country. In a first stage governments decide whether to link domestic emission permit markets to an international market. An international permit market is formed if and only if both countries agree to it. In the second stage governments decide about the amounts of emission permits which are issued to the domestic firms. In both stages governments are lobbied by domestic pressure groups which try to sway the government policy in their favor. Governments are susceptible to the interests of lobby groups, as they maximize a weighted sum of national social

[1] In fact, Australia plans to join the European Union's Emission Trading Scheme by 2015.

welfare and lobby contributions. Trading of permits – within or between countries depending on the regime choice of the first stage – takes place in the third stage.

We find that, as long as all lobby groups exhibit strictly positive contribution schedules in the second stage, both the choice of regime in the first stage and the amounts of emission permits issued in the second stage only depend on the aggregate levels of organized stakes in both countries. In particular, they are independent of the number of interest groups and the distribution of stakes among them.

In addition, we find that an increase in the influence of a particular interest group may result in a policy change which is counter to the interests of the respective lobby. The intuition behind this result is that a change in the political environment has two effects. The direct effect induces the home government to be more in favor of this lobby group's preferred regime. In addition, there is an indirect effect, as a change in the political environment changes the equilibrium emission allowance choices in both regimes and in both countries. Although the change in equilibrium allowances is in both regimes and both countries in the direction which is preferred by the lobby group whose influence rises, it may induce a change towards the lobby group's less preferred regime. If the increasing influence of the lobby group induces a change to this group's less preferred regime, the lobby group may be worse off than before. In this respect, our analysis suggests that national political influence by lobby groups has important ramifications for the political feasibility of linking national permit markets.

Our paper contributes to several strands of literature. It builds on the literature on non-cooperative international permit markets, developed by Helm (2003), Carbone, Helm and Rutherford (2009) and Helm and Pichler (2011). While these papers assume benevolent national governments, we introduce a political economy framework. Therefore, we draw on the literature on special interest groups, the "common agency" approach, originally developed by Bernheim and Whinston (1986) and extended by Grossman and Helpman in various seminal contributions (Grossman and Helpman, 1994, 1995a,b). In particular, we combine a binary regime choice and a continuous emission allowance choice, both of which are prone to lobbying by special interest groups.

Another closely related strand of literature examines the political economy of tradable emission permits and, in particular, the question whether permits should be auctioned or grandfathered in the presence of lobbying (Lai, 2007, 2008). While Lai's analysis is confined to the national level, we analyze how political competition on the national level influences international policies. In our analysis we do not consider lobbying influences on permit issuance, but rather assume an exogenously given redistribution regime of emission permit revenues.

Our paper is also closely related to the so called “strategic delegation” literature, which offers a complementary view on national political competition. In these models the principal, i.e. the median voter, elects a politician who then bargains with a foreign politician over an issue at stake. Taking these negotiations into account, the median voter may actually vote for a politician with different preferences than her own in order to manipulate the threat point in the international negotiations in her favor.[2] Strategic delegation in the context of environmental policy has been analyzed by Siqueira (2003) and Buchholz et al. (2005) who both find a bias towards politicians who are less green than the median voter. By electing a more conservative politician, the home country commits itself to a lower tax on pollution, shifting the burden of a cleaner environment to the foreign country. Taking into account emissions leakage through shifts in production, Roelfsema (2007) finds that median voters may delegate to politicians who put more weight on environmental damage than themselves, whenever their preferences for the environment are sufficiently strong compared to firms’ profits. In a more general set-up, Harstad (2010) studies the incentives to delegate to more conservative or more progressive politicians. While delegation to the former increases the bargaining position, the latter are more likely to be included in majority coalitions and hence increase the political power of their jurisdiction. The direction of delegation then depends on the design of the political system.

2.2 The model

We consider two countries, indexed by $i = 1, 2$ and $-i = \{1, 2\} \setminus i$.[3] In each country i, emissions e_i imply country-specific benefits $B_i(e_i)$ from the productive activities of a representative firm with $B_i(0) = 0$, $B_i' > 0$ and $B_i'' < 0$ for all $i = 1, 2$. Global

[2] There are fundamental differences between the common agency approach and the strategic delegation literature. Whereas the common agency set-up assumes an *incumbent government* which is swayed by interest groups to implement policies in their favor, the strategic delegation literature models the *election* of a politician, where the median voter takes into account that she might be better off by electing a politician who does not represent her own preferences because of strategic interactions of the elected politicians with other policy-makers. Thus, the common agency and the strategic delegation model represent complementary perspectives on the political process of modern democracies. In addition, although both approaches analyze principal-agent relationships, the common agency approach differs from strategic delegation in that it includes competition by the principals with their rivals for political influence. A median voter, however, never faces any competition by other voters and hence is not required to engage in rent-seeking.

[3] All our results can be generalized to n countries in a straightforward manner.

emissions, $E = e_1 + e_2$, cause strictly increasing and convex country-specific damages $D_i(E)$ with $D_i(0) = 0$ and $D_i' > 0$, $D_i'' \geq 0$ for all $E > 0$ and $i = 1, 2$.

2.2.1 Non-cooperative international climate policy

Countries set up perfectly competitive domestic emission permit markets in which each country i non-cooperatively decides on the amount of emission permits ω_i issued to its representative domestic firm. As firms in all countries i need (at least) emission permits amounting to emissions e_i, global emissions are given by the sum of emission permits issued, $E = \omega_1 + \omega_2$. Countries may agree upon linking the domestic permit markets to an international permit market, which we will refer to as the "choice of regime". Then permits issued from both countries are traded on a perfectly competitive international permit market at price p.

Environmental policy imposes an additional cost to the representative firms reducing the gross (of transfers) profits, but it generates revenues which can be redistributed in different ways. Denoting the type of regime by $R = \{I, D\}$ (*I*nternational if an international emission permit market is formed and *D*omestic otherwise), gross profits π_i^R of the representative firm and emission permit revenues T_i^R are given by:

$$\pi_i^R(\omega_1, \omega_2) = B_i(e_i^R) - p^R e_i^R \ , \qquad T_i^R(\omega_1, \omega_2) = p^R \omega_i \ . \tag{2.1}$$

We give special attention to two prominent redistribution schemes: (i) the emission permit revenues are redistributed to the representative firms, and (ii) revenues benefit the general public via a lump-sum transfer.[4]

Social welfare in country i is given by the gross profits of the representative firm, the environmental damage and the permit market revenues:

$$W_i^R(\omega_1, \omega_2) = \pi_i^R(\omega_1, \omega_2) - D_i(E) + T_i^R(\omega_1, \omega_2) = B_i(e_i^R) - D_i(E) + p^R \left[\omega_i - e_i^R\right] \ . \tag{2.2}$$

2.2.2 Political actors

Each country i is represented by a government deciding on its environmental policy. Governments face two consecutive decisions, which we model as a sequential game: (i) a binary decision whether the respective country wants to participate in an international

[4] These two cases correspond to the most common issuance and redistribution schemes: (i) permits are freely allocated to firms and (ii) emission permits are auctioned and the revenues are redistributed to the general public.

emission permit market and (ii) the choice of the level of issued permits contingent on whether an international permit market is formed. Governments in each country care about national social welfare but are also vulnerable to lobbying contributions of special interest groups.

There are M_i interest groups in country i, which exhibit different stakes in the elements of the social welfare function W_i. The degree to which interest group j is a stakeholder of the representative domestic firm is defined as $0 \leq \beta_{ij} \leq 1$. The share $0 \leq \delta_{ij} \leq 1$ characterizes the extent to which lobby group j in country i suffers from damages caused by emissions. The interest groups' stakes in the revenues from permit issuance are denoted by $0 \leq \rho_{ij} \leq 1$. Thus, the gross utility of lobby group j in country i reads:

$$U_{ij}^R(\omega_1, \omega_2) = \beta_{ij}\pi_i^R(\omega_1, \omega_2) - \delta_{ij}D_i(E) + \rho_{ij}T_i^R(\omega_1, \omega_2) \ . \tag{2.3}$$

Redistributing the emission permit revenues to the representative domestic firm implies $\rho_{ij} = \beta_{ij}$ for all $j = 1, \ldots, M_i$. For simplicity, we assume that transferring permit revenues to the general public corresponds to $\rho_{ij} = \delta_{ij}$ for all $j = 1, \ldots, M_i$.[5] The national aggregates $b_i = \sum_{j=1}^{M_i} \beta_{ij}$, $d_i = \sum_{j=1}^{M_i} \delta_{ij}$ and $r_i = \sum_{j=1}^{M_i} \rho_{ij}$ denote the share of firms' profits, environmental damages and emission permit revenues in country i which are under the control of organized special interest groups.[6]

Organized interest groups in country i offer contributions to the local government in order to sway chosen policies in their favor. As we model the two policy decisions the governments face as a sequential game, they may offer contributions for each of the policy decisions separately. Lobby groups are assumed to maximize the total payoff of their members, which is the organized stakes in national social welfare U_{ij}^R that the lobby group j in country i represents minus lobbying contributions in the first and second stage:

$$U_{ij}^R(\omega_1, \omega_2) - \left[C_{ij}^{1,R} + C_{ij}^{2,R}(\omega_1, \omega_2)\right] \ , \tag{2.4}$$

where $C_{ij}^{1,R}$ and $C_{ij}^{2,R}$ are the lobbying contributions of lobby group j in country i in the first and second stage, respectively, contingent on the implemented regime and, in case of stage-two lobbying contributions, depending on the governments' policy choices.

Governments in both countries are assumed to care about the weighted sum of national

[5] This does not hold whenever permit revenues are returned lump-sum but damages are asymetrically distributed. We thank one of the referees for pointing this out.

[6] We only consider the implications of an exogenously given redistribution scheme, as described by the exogenously given parameters ρ_{ij}. Although a model set-up is conceivable in which governments also decide about the terms of revenue redistribution, this is beyond the scope of this paper.

social welfare and lobbying contributions:

$$G_i^R(\omega_1, \omega_2) = W_i^R(\omega_1, \omega_2) + \theta_i \sum_{j=1}^{M_i} \left[C_{ij}^{1,R} + C_{ij}^{2,R}(\omega_1, \omega_2) \right] , \tag{2.5}$$

where θ_i is the relative weight the government in country i attaches to lobbying contributions compared to domestic social welfare W_i^R. As pointed out by Grossman and Helpman (1994), there is a close connection between the common agency approach employed here and the *political support* approach pioneered by Stigler (1971). In the latter framework an incumbent government seeks to maximize its chances of reelection by maximizing its political support of the different interest groups among the electorate. As a consequence, the government's utility function has as arguments the welfare that different interest groups derive depending on the chosen policy plus the deadweight loss these policies impose on the society as a whole, while contributions of interest groups do not directly enter the government's welfare. As we shall see, the common agency approach bridges the gap between interest groups' welfare and contributions, as in equilibrium – and at least in case of truthful contribution schedules – the marginal contributions offered to the government by all interest groups represent the change in the interest groups' welfare due to a marginal change in the governments' chosen policy.[7]

Who are the special interest groups that are strongly affected by national and international climate policies, and therefore have an interest to offer contributions? The enaction process of the EU Emission Trading Scheme (EU-ETS) has shown that in particular the electricity producers and large energy intensive industries – such as refining, iron, steel, aluminium, pulp and paper, and cement – are represented by influential interest groups and had a significant impact on the final design of the EU-ETS (Markussen and Svendsen, 2005). Obviously, these interest groups oppose stringent caps for greenhouse gas emissions or, if they cannot avert them, lobby for free issuance of permits. In favor of stricter emission caps are national and international environmental NGOs. In addition, these interest groups often would like to see the revenues for emission permits being earmarked for environmental projects such as fostering renew-

[7] Besides trading money for influence in the form of campaign contributions or direct compensations like in our model, the dissemination of information is the second important channel of influence for interest groups in pursuing their political goals. In the public choice literature, these different channels have either been modeled through contests for policy rents (such as rent-seeking contests, menu and other auctions and bargaining), through the transmission of strategic information (such as persuasion, signaling, screening and search) or a combination of both. An excellent survey on modeling rent-seeking contests is Nitzan (1994), while Grossman and Helpman (2001) and Winden (2003) survey the literature on special interest groups.

able energies, etc. On the consumers' side, automobile associations have established a reputation to fiercely oppose any policies that increase the costs of driving, for example, environmental taxes on driving fuels.

2.2.3 Structure of the game

We model the consecutive decisions on the choice of regime and the issuance of emission permits as a non-cooperative sequential game. In the first stage, governments of both countries simultaneously decide whether to link the domestic emission permit markets to an international emission permit market. An international permit market is set up if and only if both countries consent to it. In the second stage, the governments simultaneously decide on the amount of emission permits issued to the domestic firms. In the third stage, emission permits are traded.

In our model setup, two separate non-cooperative games take place in the first two stages: On the one hand, organized interest groups act non-cooperatively in choosing their contribution schedules to influence the respective government's policy. On the other hand, countries decide non-cooperatively on international environmental policy. As a consequence, each of the two model stages comprises a lobbying game in each country (Grossman and Helpman, 1994, 1995a), which gives rise to several consecutive sub-stages:[8]

(i) Regime choice:

   a) First, all organized lobby groups j in both countries simultaneously offer a contribution contingent on their preferred type of regime.

   b) Second, governments in both countries simultaneously decide on whether to participate in an international permit market. An international permit market is formed if and only if both countries consent to it.

   c) Third, lobby groups pay contributions contingent on the established regime.

(ii) Emission allowance choices:

   a) First, knowing the regime type established in the first stage, all organized lobby groups j in both countries simultaneously offer a contribution schedule contingent on the policy choice of the local government for a given decision of the other government.

[8] In line with Grossman and Helpman (1994, 1995a), we assume that lobby groups offer contributions only to the local government.

b) Second, governments in both countries simultaneously decide on the amount of emission permits they issue to the domestic firms.

c) Third, lobby groups pay contributions contingent on policy choice.

(iii) Permit trade:
Depending on the regime established in the first stage, emission permits are traded on national or international permit markets.

Finally, we impose the following assumptions on the benefit functions B_i and the lobbying parameters θ_i, r_i and b_i:

Assumption 2.1 (Sufficient conditions for SOCs to hold)
For the remainder of the paper, we assume

(i) *The benefit functions of both countries are* almost quadratic*:* $B_i'''(e_i) \approx 0$, $i = 1, 2$.

(ii) *The following condition holds for the lobbying parameters in both countries:*

$$r_i > \frac{1}{2}b_i - \frac{1}{2\theta_i} \ , \quad i = 1, 2 \ .$$

These assumptions are sufficient (but not necessary) conditions for all second-order conditions throughout the paper to hold. By almost quadratic, we mean that $B_i'''(e_i)$ is so small that it is irrelevant for determining the sign of all expressions in which it appears. The second condition states that the aggregate organized stakes r_i in the permit revenues must not be too small compared to the aggregate organized stakes in the profits of the organized firm. Obviously, the condition is always satisfied if $r_i = b_i$, i.e. if the permit market revenues are redistributed to the stakeholders of the representative firm.

2.3 The third stage: Permit market equilibrium

We solve the game by backward induction, starting with the third stage. In case of national emission permit markets, the market clearing condition implies that $\omega_i = e_i$ for both countries $i = 1, 2$. Profit maximization of the representative firm implies that the equilibrium permit price equals marginal benefits:

$$p_i(\omega_i) = B_i'(e_i) \ , \quad i = 1, 2 \ . \tag{2.6}$$

In case of an international permit market, there is only one permit market price implying that in equilibrium the marginal benefits of all participating countries are equal:

$$p(E) = B_1'\Big(e_1(E)\Big) = B_2'\Big(e_2(E)\Big) \ . \tag{2.7}$$

In addition, the market clearing condition

$$\omega_1 + \omega_2 = B_1'^{-1}\Big(p(E)\Big) + B_2'^{-1}\Big(p(E)\Big) = e_1(E) + e_2(E) = E \ , \tag{2.8}$$

implicitly determines the permit price $p(E)$ in the market equilibrium as a function of the total number of issued emission allowances E. Existence and uniqueness follow directly from the assumed properties of the benefit functions B_i. From equation (2.7) and $e_i(E) = B_i'^{-1}\Big(p(E)\Big)$, it follows directly that:

$$p'(E) < 0 \ , \qquad e_i'(E) \in [0, 1] \ . \tag{2.9}$$

2.4 The second stage: Permit choices

In the second stage, the regime choice of the first stage is known to all lobby groups and governments. Also the contributions $C_{ij}^{1,R}$ paid in the first stage are sunk and do not influence the governments' and the lobby groups' decisions. In the second stage, governments in both countries set non-cooperatively the levels of emission permits, while organized interest groups in each country sway the local government to choose policies in their favor by offering contribution schedules.

As outlined in Section 2.2.3, the second stage splits into several sub-stages. First, all lobby groups in all countries simultaneously offer contribution schedules $C_{ij}^{2,R}(\omega_1, \omega_2)$ to their governments, which specify the lobby contributions contingent on the policy choices ω_i and ω_{-i} of the domestic and the foreign government. Then, the governments in both countries simultaneously set the levels of emission permits ω_1 and ω_2 they issue to the representative domestic firm. Finally, lobby groups in both countries pay contributions according to the choice of emission permits to their governments.

We seek the subgame perfect Nash equilibrium of this non-cooperative game in the second stage for truthful contribution schedules of all interest groups (Bernheim and Whinston, 1986). A truthful contribution schedule offers for any change of the government's policy the corresponding change in the respective lobby group's welfare, except when the contribution would be negative.[9] In this case, we require a zero contribution

[9] This definition implies that a truthful contribution schedule follows the lobby group's payoff func-

instead:

$$C_{ij}^{2,R}(\omega_1, \omega_2) = \max\left[0, U_{ij}^R(\omega_1, \omega_2) - \bar{U}_{ij}^R\right] \ . \tag{2.10}$$

This implies that the net of contributions utility $\bar{U}_{ij}^R$ of all lobby groups is independent of the chosen policy of the government. In fact, the restriction to truthful contribution schedules boils the first sub-stage of the non-cooperative lobbying game in all countries down to the simultaneous non-cooperative choice of the base utility levels $\bar{U}_{ij}^R$. For the case of strictly positive contribution schedules, marginal contributions do not depend on $\bar{U}_{ij}^R$ and are given by $\partial C_{ij}^{2,R}(\omega_1, \omega_2)/\partial\omega_i = \partial U_{ij}^R(\omega_1, \omega_2)/\partial\omega_i$, which de facto solves the first sub-stage in the second stage of the game.[10] In the following, we restrict our attention to strictly positive contribution schedules.

2.4.1 Domestic permit markets under lobby group pressure

We first assume that no international permit market has been formed in the first stage of the game. Then, the government of country i sets the level of emission permits ω_i to maximize

$$G_i^D(\omega_1, \omega_2) = W_i^D(\omega_1, \omega_2) + \theta_i \sum_{j=1}^{M_i} \left[C_{ij}^{1,D} + C_{ij}^{2,D}(\omega_1, \omega_2)\right] \ , \tag{2.11}$$

subject to (2.6), (2.10) and given the permit choice ω_{-i} of the other country.

Assuming strictly positive contribution schedules for all lobby groups j in both countries, and recalling that $\omega_i = e_i$ and $p_i(\omega_i) = B_i'(e_i)$, the reaction function of government i is implicitly given by

$$B_i'(e_i) = \frac{1 + \theta_i d_i}{1 + \theta_i r_i} D_i'(E) + \frac{\theta_i (b_i - r_i)}{1 + \theta_i r_i} \omega_i B_i''(e_i) \ , \tag{2.12}$$

and there exists a unique Nash equilibrium of this second stage of the game.

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tion minus a constant except for the non-negativity constraint.

[10] Focusing on truthful contribution schedules may seem restrictive. However, Bernheim and Whinston (1986) showed that lobby groups suffer no loss from playing truthful contribution schedules, since each lobby group's set of best-response strategies for any given contribution schedules of all other lobby groups contains a truthful contribution schedule. Furthermore, in a game setting of complete information truthful payment schedules constitute a simple device to achieve efficiency without any player conceding his right to grab as much as she can for herself. For a detailed discussion of truthful contribution schedules, see Bernheim and Whinston (1986) and Dixit et al. (1997).

Proposition 2.1 (Unique Nash equilibrium on domestic permit markets)
For truthful and strictly positive contribution schedules of all lobby groups, there exists a unique Nash equilibrium of the game in which all countries $i = 1, 2$ *simultaneously set emission permit levels* ω_i *to maximize* (2.11) *subject to equation* (2.6) *and a given permit level* ω_{-i} *of the other country.*

The proof of Proposition 2.1 is given in the Appendix.

Equation (2.12) implies that both domestic emission levels e_i and total emissions E only depend on the aggregate levels of organized stakes b_i, d_i and r_i in the three components of social welfare in both countries and neither on the number nor the composition of lobby groups, as long as all lobby groups exhibit strictly positive equilibrium contribution schedules.

For the two redistribution schemes $r_i = b_i$ and $r_i = d_i$, the following corollary states how domestic and global emissions in the Nash equilibrium react to a change of the political environment:

Corollary 2.1 (Comparative statics of domestic permit markets)
For $r_i = b_i$ *and* $r_i = d_i$*, the following conditions hold for the levels of national emissions* e_i*,* e_{-i} *and global emissions* E *in the Nash equilibrium:*

$$\frac{de_i}{db_i} > 0 \ , \qquad \frac{de_{-i}}{db_i} < 0 \ , \qquad \frac{dE}{db_i} > 0 \ , \tag{2.13a}$$

$$\frac{de_i}{dd_i} < 0 \ , \qquad \frac{de_{-i}}{dd_i} > 0 \ , \qquad \frac{dE}{dd_i} < 0 \ , \tag{2.13b}$$

$$\frac{de_i}{d\theta_i} \gtreqless 0 \ , \qquad \frac{de_{-i}}{d\theta_i} \lesseqgtr 0 \ , \qquad \frac{dE}{d\theta_i} \gtreqless 0 \quad \Leftrightarrow \quad b_i \gtreqless d_i \ . \tag{2.13c}$$

The proof of Corollary 2.1 is given in the Appendix.

Corollary 2.1 states that domestic emission levels e_i of country i and also global emissions E are higher the higher are the organized stakes in the benefits and the lower are the organized stakes in the environmental damages in country i. An increase in θ_i increases domestic emissions e_i and total emissions E if and only if $b_i > d_i$, i.e. if the share of organized stakes is higher for benefits than for environmental damages. Moreover, domestic emission levels are strategic substitutes. If country i increases emission levels in response to a change in the political parameters b_i, d_i and θ_i, country $-i$ decreases the emission level and vice versa. However, the direct effect outweighs the indirect effect and the total emissions E follow the domestic emission level e_i. The signs of the comparative static analysis are identical for both redistribution schemes

$r_i = b_i$ and $r_i = d_i$.

2.4.2 International permit markets under lobby group pressure

If an international permit market is formed in the first stage, the government in country i chooses ω_i to maximize

$$G_i^I(\omega_1, \omega_2) = W_i^I(\omega_1, \omega_2) + \theta_i \sum_{j=1}^{M_i} \Big[C_{ij}^{1,I} + C_{ij}^{2,I}(\omega_1, \omega_2) \Big] \ , \qquad (2.14)$$

subject to equations (2.7), (2.8), (2.10) and given ω_{-i}.

Again, considering only strictly positive truthful contribution schedules and taking into account that $p(E) = B_i'\Big(e_i(E)\Big)$, the reaction function of country i is given by

$$p(E) + p'(E) \left[\omega_i - e_i(E) \right] = \frac{1 + \theta_i d_i}{1 + \theta_i r_i} D_i'(E) + \frac{\theta_i (b_i - r_i)}{1 + \theta_i r_i} p'(E) e_i(E) \ , \qquad (2.15)$$

implying the existence of a unique Nash equilibrium.

Proposition 2.2 (Unique Nash equilibrium on international permit markets) *For truthful and strictly positive contribution schedules of all lobby groups, there exists a unique Nash equilibrium of the game in which both countries simultaneously set the level of emission permits ω_i to maximize* (2.14) *subject to equations* (2.7)*,* (2.8) *and given permit levels ω_{-i} of the other country.*

The proof of Proposition 2.2 is given in the Appendix.

Again, we observe from equation (2.15) that the allowance choices ω_i and, thus, also domestic and global emissions only depend on the national levels of organized stakes b_i, d_i and r_i and neither on the number nor the composition of lobby groups, as long as all lobby groups pay strictly positive contributions in equilibrium.

For the effects of a change in the political environment on the issuance of emission permits, we find similar results as in the case of non-linked domestic permit markets. On international permit markets, however, the permit choices of the two countries are not necessarily strategic substitutes. Defining $FOC_{\omega_i}^{-i} \equiv \partial^2 G_{-i}^I(\omega_1, \omega_2)/(\partial \omega_i \partial \omega_{-i})$, we obtain:

$$FOC^{-i}_{\omega_i} = p'(E)\left[(1+\theta_{-i}r_{-i}) - (1+\theta_{-i}b_{-i})e'_{-i}(E)\right] - (1+\theta_{-i}d_{-i})D''_{-i}(E) + \mathcal{O}\Big(p''(E)\Big) \ , \tag{2.16}$$

where $\mathcal{O}\Big(p''(E)\Big)$ denotes terms which depend on $p''(E)$ and are approximately zero by virtue of Assumption 2.1. If $FOC^{-i}_{\omega_i} > 0$ then ω_i and ω_{-i} are strategic complements implying that the government in country $-i$ reacts by increasing emission permits ω_{-i} if ω_i rises. This can only happen if b_{-i} exceeds r_{-i} and $(1+\theta_{-i}d_{-i})D''_{-i}(E)$ is sufficiently small.

Corollary 2.2 (Comparative statics of international permit markets)
For $r_i = b_i$ and $r_i = d_i$, the following conditions hold for the levels of emission allowances ω_i, ω_{-i} and global emissions E in the Nash equilibrium:

$$\frac{d\omega_i}{db_i} > 0 \ , \quad \text{sgn}\left(\frac{d\omega_{-i}}{db_i}\right) = \text{sgn}\left(FOC^{-i}_{\omega_i}\right)\text{sgn}\left(\frac{d\omega_i}{db_i}\right) \ , \quad \frac{dE}{db_i} > 0 \ , \tag{2.17a}$$

$$\frac{d\omega_i}{dd_i} < 0 \ , \quad \text{sgn}\left(\frac{d\omega_{-i}}{dd_i}\right) = \text{sgn}\left(FOC^{-i}_{\omega_i}\right)\text{sgn}\left(\frac{d\omega_i}{dd_i}\right) \ , \quad \frac{dE}{dd_i} < 0 \ , \tag{2.17b}$$

$$\frac{d\omega_i}{d\theta_i} \gtreqless 0 \ , \quad \text{sgn}\left(\frac{d\omega_{-i}}{d\theta_i}\right) = \text{sgn}\left(FOC^{-i}_{\omega_i}\right)\text{sgn}\left(\frac{d\omega_i}{d\theta_i}\right) \ , \quad \frac{dE}{d\theta_i} \gtreqless 0 \quad \Leftrightarrow \quad b_i \gtreqless d_i \ . \tag{2.17c}$$

The proof of Corollary 2.2 is given in the Appendix.

Defining *politically adjusted* marginal damages

$$\tilde{D}'_i(E) = \frac{1+\theta_i d_i}{1+\theta_i r_i}D'_i(E) + \frac{\theta_i(b_i - r_i)}{1+\theta_i r_i}p'(E)e_i(E) \ , \tag{2.18}$$

we can interpret the influence of lobbying in the second stage as leading to a distorted perception of environmental damages by the government, depending on the redistribution scheme. Summing up the reaction functions (2.15) for both countries, we find that the equilibrium permit price equals the average politically adjusted marginal damage:

$$p(E) = \frac{1}{2}\left[\tilde{D}'_i(E) + \tilde{D}'_{-i}(E)\right] \ . \tag{2.19}$$

Inserting this equation for the permit price back into the reaction function (2.15) yields the straightforward generalization of Proposition 1 of Helm (2003):

$$\omega_i - e_i(E) = -\frac{1}{p'(E)}\left\{\frac{1}{2}\left[\tilde{D}'_i(E) + \tilde{D}'_{-i}(E)\right] - \tilde{D}'_i(E)\right\} \ , \tag{2.20}$$

implying that the country with above average politically adjusted marginal damages buys permits from the country with below average politically adjusted marginal damages. Thus, our analysis provides a new rationale for international permit trade: Even economically identical countries can gain by trading on international permit markets if politically adjusted marginal damages in both countries differ due to different political environments.

2.4.3 Global emissions under domestic and international permit markets

Similar to Proposition 2 of Helm (2003), we find that global emissions on an international permit market can be higher or lower compared to global emissions in case of two non-linked domestic permit markets. We denote the Nash equilibrium in case of domestic permit markets by $\omega_i^D = e_i^D$, E^D, and by ω_i^I, E^I in case of an international permit market. Introducing the abbreviations $\sigma_i \equiv (1+\theta_i d_i)/(1+\theta_i r_i)$ and $\kappa_i \equiv \theta_i(b_i - r_i)/(1+\theta_i r_i)$, and summing up the reaction functions (2.12) and (2.15) over both countries, we obtain

$$B_i'(e_i^D) + B_{-i}'(e_{-i}^D) - \kappa_i p_i'(\omega_i^D)e_i^D - \kappa_{-i}p_{-i}'(\omega_{-i}^D)e_{-i}^D = \sigma_i D_i'(E^D) + \sigma_{-i}D_{-i}'(E^D) \ , \tag{2.21a}$$

$$B_i'\Big(e_i(E^I)\Big) + B_{-i}'\Big(e_{-i}(E^I)\Big) - \kappa_i p'(E^I)e_i(E^I) - \kappa_{-i}p'(E^I)e_{-i}(E^I) = \sigma_i D_i'(E^I) + \sigma_{-i}D_{-i}'(E^I) \ . \tag{2.21b}$$

Then, the following relationship between global emissions in the international and domestic permit market regime follows directly from $\tilde{D}_i'' \geq 0$:

$$E^D \gtreqless E^I \quad \Leftrightarrow \quad B_i'(e_i^D) + B_{-i}'(e_{-i}^D) - \kappa_i p_i'(\omega_i^D)e_i^D - \kappa_{-i}p_{-i}'(\omega_{-i}^D)e_{-i}^D \gtreqless B_i'\Big(e_i(E^D)\Big) + B_{-i}'\Big(e_{-i}(E^D)\Big) - p'(E^D)\Big[\kappa_i e_i(E^D) + \kappa_{-i}e_{-i}(E^D)\Big] \ . \tag{2.22}$$

2.4.4 Equilibrium lobby contributions

Finally, we determine the equilibrium lobbying contributions in the second stage. In the equilibrium of each regime R, the government must be indifferent with respect to the participation of any individual lobby group in the lobbying game, as lobbies want to contribute as little as possible and the government can never be worse off with lobbying than without (Grossman and Helpman, 1995a):

$$W_i^R(\omega_1^R, \omega_2^R) + \theta_i \sum_{j=1}^{M_i} C_{ij}^{2,R}(\omega_1^R, \omega_2^R) = W_i^R(\omega_1^{-k}, \omega_2^{-k}) + \theta_i \sum_{\substack{j=1 \\ j \neq k}}^{M_i} C_{ij}^{2,R}(\omega_1^{-k}, \omega_2^{-k}) \ , \quad (2.23)$$

where ω_i^{-k} indicate equilibrium permit levels that would arise if lobby group k did not offer any contributions. Then, the following proposition holds for the equilibrium contributions of all lobbying groups.

Proposition 2.3 (Equilibrium contributions in the second stage)
For truthful and strictly positive contribution schedules of all lobby groups, the equilibrium contribution in regime R of lobby group k in country i yields:

$$C_{ik}^{2,R}(\omega_1^R, \omega_2^R) = \frac{1}{\theta_i}\left[W_i^R(\omega_1^{-k}, \omega_2^{-k}) - W_i^R(\omega_1^R, \omega_2^R)\right] + (b_i - \beta_{ik})\left[B_i(e_i^{-k}) - B_i(e_i^R)\right]$$
$$- (d_i - \delta_{ik})\left[D_i(E^{-k}) - D_i(E^R)\right] - (r_i - \rho_{ik})\left[p^{-k}(e_i^{-k} - \omega_i^{-k}) - p^R(e_i^R - \omega_i^R)\right] \ . \quad (2.24)$$

The proof of Proposition 2.3 is given in the Appendix.

A particular lobby group k has to compensate the government twofold: First, it has to recompense proportionally for the loss (gain) in domestic welfare attributable to the change in issued permit levels due to the lobby's influence. The proportionality factor equals $1/\theta_i$ since lobby contributions enter the government's objective function with a weight of θ_i. Second, lobbies have to compensate for the loss (gain) in contributions from all other lobbies due to the change in the government's policy choice resulting from the lobby's influence.

Proposition 2.3 yields an important insight. While the equilibrium levels of emission permits only depend on the aggregate national strength b_i, d_i and r_i of lobbying groups, the equilibrium contributions of individual lobby groups also depend on the absolute number of lobby groups and their composition. It can also be shown that the aggregate lobbying contributions the government in country i receives in the second stage depend, in general, on the number and composition of pressure groups within each country.

2.5 The first stage: To link or not to link

Having characterized the level of emission permits on domestic and international permit markets depending on the political situation, we now move on to analyze the governments' decision in the first stage. The decision process in the first stage is also prone to be affected by lobbies, as interest groups either gain or lose depending on whether an international permit market is formed. As a consequence, also the first stage splits into several consecutive sub-stages: First, lobby groups in all countries simultaneously offer contributions contingent on the established regime. As regime choice is binary, lobbies offer a non-negative payment for their preferred regime (and zero for the other regime). Second, governments simultaneously decide whether to form an international permit market which only comes into existence if both countries consent to it. Finally, lobby groups pay contributions.

2.5.1 Unilateral stances

The preferred regime of the government in country i is independent of the preferred regime in country $-i$. Thus, regime choices of governments (unilateral stances in the terminology of Grossman and Helpman, 1995a) are dominant strategies and the lobbying games in both countries can be analyzed separately.

Governments choose the regime R to maximize their total payoff G_i^R, which is given by the social welfare of country i and the weighted lobbying contributions in the first and second stage. For establishing regime R, a lobby is willing to pay to the government at most as much as it gains in the second stage by a change of regime from the alternative regime $\bar{R}$ to R, which is given by the difference in the lobby's utilities between both regimes net of lobbying contributions in the second stage:

$$\Delta U_{ij}^{R,\bar{R}} \equiv U_{ij}^{R}(\omega_1^R, \omega_2^R) - C_{ij}^{2,R}(\omega_1^R, \omega_2^R) - U_{ij}^{\bar{R}}(\omega_1^{\bar{R}}, \omega_2^{\bar{R}}) + C_{ij}^{2,\bar{R}}(\omega_1^{\bar{R}}, \omega_2^{\bar{R}}) \ . \tag{2.25}$$

Thus, lobby group j in country i supports regime R if and only if $\Delta U_{ij}^{R,\bar{R}} > 0$ which also implies that $\Delta U_{ij}^{\bar{R},R} < 0$. As contributions must be non-negative, the contribution of lobby j supporting regime R is given by:

$$C_{ij}^{1,R} \in [0, \Delta U_{ij}^{R,\bar{R}}] \ , \quad C_{ij}^{1,\bar{R}} = 0 \ . \tag{2.26}$$

First, we examine under which conditions no contributions of all lobby groups in the first stage is a unilateral stance. Therefore, suppose that without lobbying in the first stage the government in country i supports regime R. Then, $G_{i0}^{R} > G_{i0}^{\bar{R}}$, where G_{i0}^{R} denotes the government's payoff without the lobbying contributions in the first stage under regime R. Given that all other lobby groups in country i do not contribute, not contributing itself is a best response for lobby group j if and only if

$$G_{i0}^{R} - G_{i0}^{\bar{R}} > \theta_i \Delta U_{ij}^{\bar{R},R} \; . \tag{2.27}$$

If inequality (2.27) holds, then no single lobby group can profitably contribute enough in the first stage to unilaterally sway the government to change its support from regime R to regime $\bar{R}$. Thus, no contributions from all lobby groups in the first stage is a unilateral stance if and only if condition (2.27) holds simultaneously for all organized lobby groups in country i. Grossman and Helpman (1995a) call this equilibrium an *unpressured* unilateral stance.

Second, we examine the conditions under which there exists a unilateral stance with positive lobbying contributions in the first stage, which Grossman and Helpman (1995a) call a *pressured* unilateral stance. For a pressured stance the government must be indifferent with respect to the choice of regime, i.e.,

$$G_{i0}^{R} + \theta_i \sum_{j=1}^{M_i} C_{ij}^{1,R} = G_{i0}^{\bar{R}} + \theta_i \sum_{j=1}^{M_i} C_{ij}^{1,\bar{R}} \; , \tag{2.28}$$

as otherwise it would be possible for the lobby groups on the winning side to reduce their lobbying contributions and still having their preferred regime choice being adopted. Moreover, lobby groups on the losing side would offer their total net gain in case the government adopted their preferred choice. If this were not true, the losers could sway the government in favor of their preferred regime choice by increasing their contributions. Let S_R ($S_{\bar{R}}$) be the set of lobbies which support regime R ($\bar{R}$), i.e. for all $j \in S_R$ ($S_{\bar{R}}$), $\Delta U_{ij}^{R,\bar{R}} > (<)\ 0$ holds. Then, a unilateral stance with positive lobbying contributions in favor of regime R requires:

$$G_{i0}^{R} + \theta_i \sum_{j \in S_R} \Delta U_{ij}^{R,\bar{R}} > G_{i0}^{\bar{R}} + \theta_i \sum_{j \in S_{\bar{R}}} \Delta U_{ij}^{\bar{R},R} \; . \tag{2.29}$$

This condition states that the *potential* payoff the government is able to collect under regime R must be higher than the *potential* payoff under the alternative regime. The sum of actual contributions is determined by equation (2.28).

Note that condition (2.29) is necessary but not sufficient for a pressured stance in favor of regime R to exist. In addition we need that

$$G_{i0}^{R} < G_{i0}^{\bar{R}} + \theta_i \sum_{j \in S_{\bar{R}}} \Delta U_{ij}^{\bar{R},R} \; ; \tag{2.30}$$

otherwise, the supporters of regime R could refrain from positive lobbying contributions and still have their preferred regime adopted, and we would be back to an unpressured stance.

For a pressured unilateral stance only the sum of lobbying contributions of all winning lobby groups is determined but not its distribution among individual lobby groups. Thus, there exist, in general, a continuum of pressured unilateral stances, which differ in individual contributions but coincide in the sum of contributions and the adopted regime choice.

2.5.2 The choice of regime

Both an unpressured and a pressured unilateral stance may exist simultaneously. This holds if condition (2.27) holds for one regime $R = \{D, I\}$ and at the same time conditions (2.29) and (2.30) hold for the same or the other regime. If, in addition,

$$G_{i0}^{\bar{R}} < G_{i0}^{R} < G_{i0}^{\bar{R}} + \theta_i \sum_{j \in S_{\bar{R}}} \Delta U_{ij}^{\bar{R},R} \; , \tag{2.31}$$

then both stances select the same regime R. Otherwise, there exists a pressured stance in favor of regime R and an unpressured stance supporting regime $\bar{R}$. As Grossman and Helpman (1995a) pointed out, in the case of coexistence unpressured stances are not coalition-proof, a notion introduced by Bernheim et al. (1987). Thus, allowing for a minimum level of communication between the lobby groups eliminates unpressured stances whenever there are also pressured stances. As a consequence, we assume that the pressured stance prevails unless there exists only an unpressured stance. Then, the following proposition holds:

Proposition 2.4 (Regime choice and distribution of organized stakes)
For truthful and strictly positive equilibrium contributions of all lobby groups in the second stage, the choice of regime only depends on the aggregate organized stakes b_i, d_i and r_i in both countries.

The proof is given in the Appendix.

The intuition for this result is that the necessary condition (2.29) for the existence of a pressured stance does not depend on the distribution of stakes as long as the national aggregates are constant. This implies that whenever there exists a pressured stance, the selected regime R only depends on the national aggregates of organized stakes. However, for a pressured stance in favor of R to exist, also the necessary condition (2.30) has to hold. In fact, this condition does, in general, depend on the distribution of organized stakes β_{ij}, δ_{ij} and ρ_{ij}. But if condition (2.29) holds for regime R while condition (2.30) is violated, then there exists an unpressured stance in favor of R. Of course, there may be a pressured stance in favor of regime R and an unpressured stance in favor of regime $\bar{R}$. But assuming that pressured stances beat unpressured stances, as discussed above, again regime R would be selected.

In summary, condition (2.29), which only depends on the aggregate organized stakes, always holds for one of the two regimes and this regime is also the regime choice of the government (or the government is indifferent between both regimes). However, the distribution of organized stakes β_{ij}, δ_{ij} and ρ_{ij} among individual lobby groups determines whether the selected regime is a pressured or unpressured stance. It also influences the contributions in the first stage and, thus, the government payoffs and the lobby groups' net utilities.

2.5.3 International permit markets

Having established each country's choice of regime, it is now straightforward to characterize the conditions under which an international permit market is established. By definition, an international permit market only forms if both countries consent to it, i.e. if regime $R = I$ is a unilateral stance in both countries. By virtue of equation (2.29) and Proposition 2.4, a permit market is thus established if and only if the following condition holds for both countries simultaneously:

$$\Delta G_i = W_i^I(\omega_1^I, \omega_2^I) - W_i^D(\omega_1^D, \omega_2^D) + \theta_i \left[\sum_{j=1}^{M_i} U_{ij}^I(\omega_1^I, \omega_2^I) - \sum_{j=1}^{M_i} U_{ij}^D(\omega_1^D, \omega_2^D) \right] > 0 \,. \quad (2.32)$$

As already pointed out by Proposition 4 in Helm (2003), there are three possible cases: (i) The international permit market regime may lead to lower total emissions and higher payoffs for the governments of both countries. (ii) Even if total emissions were lower, an international permit market may not be established because the government's payoff in one of the countries is lower compared to domestic permit markets. (iii) Although total emissions were lower under domestic permit markets, both governments may consent to an international permit market because their payoffs are higher.

In the following, we analyze how the likelihood of establishing an international permit market depends on the political parameters by differentiating equation (2.32) with respect to θ_i, b_i, d_i and r_i. This likelihood is not only determined by the reaction of the home country where the political change takes place but also by the reaction of the other country to a change in its neighbor's political environment, as the following corollary states.

Corollary 2.3 (Comparative statics of regime choice)
For the condition for a unilateral stance in favor of an international permit market in country i, it holds:[11]

$$\frac{d\Delta G_i}{dx_i} = \frac{d(\theta_i b_i)}{dx_i}\Delta\pi_i - \frac{d(\theta_i d_i)}{dx_i}\Delta D_i + \frac{d(\theta_i r_i)}{dx_i}\Delta T_i + \frac{d\Delta G_i}{d\omega_{-i}^I}\frac{d\omega_{-i}^I}{dx_i} - \frac{d\Delta G_i}{d\omega_{-i}^D}\frac{d\omega_{-i}^D}{dx_i}, \tag{2.33a}$$

$$\frac{d\Delta G_{-i}}{dx_i} = \frac{d\Delta G_{-i}}{d\omega_i^I}\frac{d\omega_i^I}{dx_i} - \frac{d\Delta G_{-i}}{d\omega_i^D}\frac{d\omega_i^D}{dx_i}, \tag{2.33b}$$

where $x \in \{\theta, b, d, r\}$ denotes one of the political parameters and $\Delta\pi_i = \pi_i^I(\omega_1^I, \omega_2^I) - \pi_i^D(\omega_1^D, \omega_2^D)$, $\Delta D_i = D_i(E^I) - D_i(E^D)$ and $\Delta T_i = T_i^I(\omega_1^I, \omega_2^I) - T_i^D(\omega_1^D, \omega_2^D)$ gains/losses of the respective stakes from international trade.

A marginal change in one of the political parameters in country i has a direct effect on the condition for a unilateral stance in favor of an international permit market by changing the weight which the payoff functions of the respective stakes receive (first three terms in equation (2.33a)) which is confined to the home country. In addition, indirect effects in both countries arise that change the equilibrium allowance choices under both regimes. These effects may be of opposite sign compared to the direct effect, and they can have the same or different signs in the two countries. As a consequence, although the direct effect may go in favor of the regime with lower (higher) global emissions, the marginal change in ΔG_i and/or ΔG_{-i} may go towards the regime with higher (lower) global emissions. If the indirect effects oppose the direct effect and are sufficiently strong, we get the counterintuitive result of the following proposition.

Proposition 2.5 (Lobbying may backfire)
An increase in the influence of organized interest groups favoring higher (lower) global emissions may actually result in a decrease (increase) of global emissions through a

[11] Note that $d\Delta G_i/d\omega_i^R = 0$ due to the first-order conditions of the second stage.

change in their home country's and/or the foreign country's unilateral stance.

The proof of Proposition 2.5 is given in the Appendix.

The intuition is as follows. Suppose the current regime is the regime with higher global emissions. Suppose further that in country i organized interest groups in favor of higher emissions gain influence in government i's decision. This influence on government i causes a direct effect in favor of the regime with higher global emissions. In addition, global emissions in both regimes increase (but, in general, to different degrees), leading to indirect effects in both countries. These may go in the opposite direction of the direct effect, i.e. they may influence the governments in any of the two countries in favor of the regime with lower global emissions, and may even outweigh the direct effect. If the indirect effect is strong enough to change the regime choice in at least one country, this may lead to a regime change to the regime with lower global emissions. In this case, global emissions may be lower compared to the initial regime.

2.6 Discussion

Within our framework of legislative lobbying, we found that both the choice of regime in the first stage and the amount of emission allowances issued in the second stage only hinge on the aggregate organized stakes b_i, d_i and r_i of the different components of social welfare within a country and not on their distribution among different interest groups. However, our formal results hinge on several assumptions.

First, we considered Assumption 2.1 to hold. Interpreting the benefits from emissions as the negative of the corresponding abatement costs, the empirical literature finds that, at least with respect to climate change, abatement cost curves can be well approximated by quadratic functions (e.g., Klepper and Peterson 2006). When emission permit revenues are redistributed to the firms – for example by grandfathering emission allowances, which is the most common practice so far – the second condition of Assumption 2.1 is always satisfied.

Second, we assumed strictly positive lobbying contributions in the second stage of all lobby groups. What would happen if we relaxed this assumption? Consider a lobby group k in country i refraining from offering contributions in equilibrium. Then the amount of emission allowances issued in equilibrium is determined by $\hat{b}_i = b_i - \beta_{ik}$, $\hat{d}_i = d_i - \delta_{ik}$ and $\hat{r}_i = r_i - \rho_{ik}$ instead of b_i, d_i and r_i. Thus, all our results still hold for the adjusted aggregate stakes $\hat{b}_i$, $\hat{d}_i$ and $\hat{r}_i$. However, according to Proposition 2.3, the contribution schedules offered by the lobby groups and, in general, also the sum of contributions the government receives depend on the distribution of aggregate organized stakes among individual interest groups. As a consequence, both the choice of regime and the choice of emission allowances are not immune to a redistribution of given aggregate stakes b_i, d_i and r_i among different interest groups if this redistribution alters the adjusted aggregate stakes $\hat{b}_i$, $\hat{d}_i$ and $\hat{r}_i$.

It can be easily verified that all our model results would still hold if there were no influence from special interest groups but governments maximized $\hat{G}_i^R = \hat{\pi}_i^R - \hat{D}_i + \hat{T}_i^R$ with $\hat{\pi}_i^R = (1 + \theta_i b_i)\pi_i^R$, $\hat{D}_i = (1 + \theta_i d_i)D_i$ and $\hat{T}_i^R = (1 + \theta_i r_i)T_i^R$. Thus, the influence of legislative lobbying can be interpreted as adjusting the incumbent governments' perception of the three different components of social welfare.[12] This has an important consequence: All our results – in particular that the increase in influence of a special interest group may result in a policy change which is counter to the interests of this group – are not only restricted to the influence of legislative lobbying, but extend to all influences that alter governments' perceptions of firm profits, environmental damages and transfers. For example, damage perception may change because of increasing (or decreasing) environmental awareness of the voters and/or the government, or new scientific intelligence on the harmfulness of emissions.

In particular, this challenges the conventional wisdom that higher environmental awareness leads to lower global emissions and acts as a partial remedy to failures in the international coordination of public goods problems (e.g. Franzen, 2003). Indeed, an increase in environmental awareness in one country (which corresponds to an increase in $\hat{D}_i$ in our model framework) reduces global emissions in both regimes but may, at the same time, induce a switch from the regime with lower to the regime with higher global emissions. If the indirect outweighs the direct effect, then global emissions increase with environmental awareness.

In this regard, our model extends the literature on counterintuitive effects of rising environmentalism. In a coalition formation game, Endres (1997) and Endres and Finus (1998) find that increasing environmental awareness has a positive effect on the reduction targets that are bargained within an international environmental agreement but may also increase free-riding incentives and hence lead to higher stability requirements. Within a framework of international trade and environmental policy, Conconi (2003) concludes that lobbies may reduce their efforts for a higher domestic pollution

[12] In a strategic delegation framework, for example, median voters would elect governments with a particular perception on the three components of social welfare that do not necessarily reflect their own preferences. How the preferences of the elected governments and the median voters differ, depends on the particular model set-up.

tax if they are aware of the corresponding emissions leakage. In a similar setting, Aidt (2005) shows that rising environmentalism is not able to prevent an increase in total pollution, even if pollution is immobile, when green lobbies are sufficiently concerned about pollution abroad.

2.7 Conclusion

We have analyzed the non-cooperative formation of an international emission permit market in a setting of political competition by national interest groups. We find that for both the continuous choice of emission allowances in the second stage and the binary choice whether an international permit market is formed only the aggregate levels of organized stakes in each country matter and not their distribution among individual lobby groups. In addition, an increase in lobbying influence by a particular lobby group may weaken the support for the interest group's preferred regime in both countries, thwarting the lobby group's efforts.

Although we found that for given national levels of organized stakes the equilibrium outcome is independent of the number and composition of individual special interest groups, this does not hold for equilibrium contributions and payoffs. In fact, we presume that lobbies with the same interests exert a positive externality on each other. Then, a higher fragmentation of such lobbies would effectively reduce equilibrium contributions which the government is able to collect. However, the investigation of this issue is left to future research.

Our analysis has focused on international climate policy by non-cooperative countries. There are, however, some notable exceptions to the extreme case of non-cooperation, one of them being the European Union which introduced a permit trading system in 2005. Thus, another promising agenda for future research is the investigation of cooperative international climate policies under political pressure from special interest groups.

2.8 Appendix

Proof of Proposition 2.1

(i) Existence: By virtue of Assumption 2.1, the maximization problem of country i is strictly concave:

$$\mathrm{SOC}_i = (1+\theta_i r_i)B_i''(e_i) - (1+\theta_i d_i)D_i''(E) - \theta_i(b_i - r_i)B_i''(e_i) - \theta_i(b_i - r_i)\omega_i B_i'''(e_i) < 0 \;. \tag{2.A.1}$$

Thus, for all countries $i = 1, 2$, the reaction function yields a unique best response for any given choice ω_{-i} of the other country. This guarantees the *existence* of a Nash equilibrium.

(ii) Uniqueness: Solving the best response functions (2.12) for e_i and summing up over both countries yields the following equation for the aggregate emissions E:[13]

$$E = \sum_{i=1}^{2} B_i'^{-1}\left(\frac{1+\theta_i d_i}{1+\theta_i r_i} D_i'(E) + \frac{\theta_i(b_i - r_i)}{(1+\theta_i r_i)}\omega_i B_i''(e_i)\right) \;. \tag{2.A.2}$$

As the left-hand side is strictly increasing and the right-hand side is strictly decreasing in E, there exists a unique level of total emissions E^D in the Nash equilibrium. Substituting back into the reaction functions yields the unique Nash equilibrium (ω_1^D, ω_2^D).

□

Proof of Corollary 2.1

Introducing the abbreviation

$$\begin{aligned}\Gamma_i = {} & [1+\theta_i(2r_i - b_i)]\, B_i''(\omega_i)\mathrm{SOC}_{-i} \\ & - [1+\theta_{-i}(2r_{-i} - b_{-i})]\, B_{-i}''(\omega_{-i})(1+\theta_i d_i)D_i''(E) > 0\end{aligned}$$

by virtue of Assumption 2.1, and applying the implicit function theorem to the first-order conditions FOC_i, equation (2.12), for both countries, we derive:

$$\frac{d\omega_i}{dx_i} = -\frac{\mathrm{SOC}_{-i}}{\Gamma_i}\frac{d\mathrm{FOC}_i}{dx_i}, \tag{2.A.3a}$$

$$\frac{d\omega_{-i}}{dx_i} = -\frac{(1+\theta_{-i}d_{-i})D_{-i}''(E)}{\Gamma_i}\frac{d\mathrm{FOC}_i}{dx_i} \;, \tag{2.A.3b}$$

---

[13] As all marginal benefit functions B_i' are strictly and monotonically decreasing, the inverse functions $B_i'^{-1}$ exist and are also strictly and monotonically decreasing.

$$\frac{dE}{dx_i} = \frac{d\omega_i}{d\theta_i} + \frac{d\omega_{-i}}{d\theta_i} = -\frac{\text{SOC}_{-i} + (1+\theta_{-i}d_{-i})D''_{-i}(E)}{\Gamma_i}\frac{d\text{FOC}_i}{dx_i}\ , \tag{2.A.3c}$$

where $x \in \{\theta, b, d\}$ denotes one of the political parameters and the derivatives of the first-order conditions, $d\text{FOC}_i/d\Box_i$, in the two cases $r_i = b_i$ and $r_i = d_i$ are as follows:

$$\frac{d\text{FOC}_i^{r_i=b_i}}{d\theta_i} = b_i B'_i(e_i) - d_i D'_i(E), \quad \frac{d\text{FOC}_i^{r_i=d_i}}{d\theta_i} = -\frac{B'_i(e_i) - D'_i(E)}{\theta_i}\ , \tag{2.A.4a}$$

$$\frac{d\text{FOC}_i^{r_i=b_i}}{db_i} = \theta_i B'_i(e_i), \quad \frac{d\text{FOC}_i^{r_i=d_i}}{db_i} = -\theta_i\omega_i B''_i(\omega_i)\ , \tag{2.A.4b}$$

$$\frac{d\text{FOC}_i^{r_i=b_i}}{dd_i} = -\theta_i D'_i(E), \quad \frac{d\text{FOC}_i^{r_i=d_i}}{dd_i} = \theta_i\left[B'_i(e_i) - D'_i(E)\right] + \theta_i\omega_i B''_i(\omega_i)\ . \tag{2.A.4c}$$

For the signs of equations (2.A.4), we used the first-order conditions to find:

$$b_i B'_i(e_i) - d_i D'_i(E) \gtreqless 0 \quad \Leftrightarrow \quad B'_i(e_i) - D'_i(E) \lesseqgtr 0 \quad \Leftrightarrow \quad b_i \gtreqless d_i \tag{2.A.5}$$

To determine the sign of $\text{dFOC}_i^{r_i=d_i}/\text{d}d_i$, we re-wrote the first-order condition to yield:

$$\theta_i\omega_i B''_i(\omega_i) = \theta_i\frac{b_i}{d_i}\omega_i B''_i(\omega_i) - \left[\frac{1}{d_i} + \theta_i\right]\left[B'_i(e_i) - D'_i(E)\right]. \tag{2.A.6}$$

Then, even if $[B'_i(e_i) - D'_i(E)] > 0$, we have:

$$\theta_i\omega_i B''_i(\omega_i) < -\theta_i\left[B'_i(e_i) - D'_i(E)\right] \quad \Rightarrow \quad \frac{\text{dFOC}_i^{r_i=d_i}}{\text{d}d_i} < 0. \tag{2.A.7}$$

Inserting equations (2.A.4) into equations (2.A.3) yields Corollary 2.1. □

Proof of Proposition 2.2

(i) Existence: By virtue of Assumption 2.1 and as $e'_i(E) \in [0,1]$, the maximization problem of country i is strictly concave:

$$\begin{aligned}\text{SOC}_i = p'(E)\{(2 + 2\theta_i r_i - (1+\theta_i b_i)e'_i(E)\} - (1+\theta_i d_i)D''_i(E) \\ + p''(E)[(1+\theta_i r_i)\omega_i - (1+\theta_i b_i)e_i(E)] < 0\ .\end{aligned} \tag{2.A.8}$$

Thus, for all countries $i = 1, 2$, the reaction function yields a unique best response for any given choice ω_{-i} of the other countries, which guarantees the *existence* of a Nash equilibrium.

(ii) Uniqueness: Summing up the reaction function (2.15) over both countries yields the following condition, which holds in the Nash equilibrium:

$$2p(E) = \sum_{j=1}^{2} \frac{1+\theta_j d_j}{1+\theta_j r_j} D_j'(E) + p'(E) \sum_{j=1}^{2} \frac{\theta_j (b_j - r_j) e_j'(E)}{1+\theta_j r_j} \ . \tag{2.A.9}$$

The left-hand side is strictly decreasing in E, while the right-hand side is strictly increasing in E as $p''(E) \approx 0$ by virtue of Assumption 2.1. Thus, there exists a unique level of total emission allowances E^I in the Nash equilibrium. Inserting E^I back into the reaction function (2.15) yields the unique equilibrium allowance choices $(\omega_i^I, \omega_{-i}^I)$.

□

Proof of Corollary 2.2

Introducing the abbreviation

$$\Lambda_i = p'(E) \left[(1+\theta_i r_i)\mathrm{SOC}_{-i} + (1+\theta_{-i} r_{-i})\mathrm{SOC}_i\right] > 0 \ , \tag{2.A.10}$$

and applying the implicit function theorem to the first-order conditions FOC_i, equation (2.15), for both countries, we derive:

$$\frac{d\omega_i}{dx_i} = -\frac{\mathrm{SOC}_{-i}}{\Lambda_i} \frac{d\mathrm{FOC}_i}{dx_i}, \tag{2.A.11a}$$

$$\frac{d\omega_{-i}}{dx_i} = \frac{FOC_{\omega_i}^{-i}}{\Lambda_i} \frac{d\mathrm{FOC}_i}{dx_i} \ , \tag{2.A.11b}$$

$$\frac{dE}{dx_i} = \frac{d\omega_i}{dx_i} + \frac{d\omega_{-i}}{dx_i} = \frac{FOC_{\omega_i}^{-i} - \mathrm{SOC}_{-i}}{\Lambda_i} \frac{d\mathrm{FOC}_i}{dx_i} \ , \tag{2.A.11c}$$

where $x \in \{\theta, b, d\}$ denotes one of the political parameters and

$$\begin{aligned} FOC_{\omega_i}^{-i} = {} & p'(E) \Big[(1+\theta_{-i} r_{-i}) - (1+\theta_{-i} b_{-i}) e_{-i}'(E)\Big] - (1+\theta_{-i} d_{-i}) D_{-i}''(E) \\ & + p''(E) \left[(1+\theta_{-i} r_{-i})\omega_{-i} - (1+\theta_{-i} b_{-i}) e_{-i}(E)\right] \gtreqless 0 \ , \end{aligned} \tag{2.A.12}$$

as indicated by equation (2.16).

The derivatives of the first-order conditions, $d\mathrm{FOC}_i/d\square_i$, in the two cases $r_i = b_i$ and $r_i = d_i$ are as follows:

$$\begin{aligned} \frac{d\mathrm{FOC}_i^{r_i=b_i}}{d\theta_i} &= b_i \left\{p(E) + p'(E)\left[\omega_i - e_i(E)\right]\right\} - d_i D_i'(E) \ , \\ \frac{d\mathrm{FOC}_i^{r_i=d_i}}{d\theta_i} &= d_i \left[p(E) + p'(E)\omega_i - D_i'(E)\right] - b_i p'(E) e_i(E) \ , \end{aligned} \tag{2.A.13a}$$

$$\frac{d\mathrm{FOC}_i^{r_i=b_i}}{db_i} = \theta_i \{p(E) + p'(E)\left[\omega_i - e_i(E)\right]\} \ , \ \frac{d\mathrm{FOC}_i^{r_i=d_i}}{db_i} = -\theta_i p'(E) e_i(E) \ , \tag{2.A.13b}$$

$$\frac{d\text{FOC}_i^{r_i=b_i}}{dd_i} = -\theta_i D_i'(E) \ , \quad \frac{d\text{FOC}_i^{r_i=d_i}}{dd_i} = \theta_i \left[p(E) + p'(E)\omega_i - D_i'(E)\right] \ . \qquad (2.A.13c)$$

For $r_i = b_i$, the signs of equations (2.A.13a) and (2.A.13b) can be found by re-writing the first-order condition as follows:

$$(1 + \theta_i b_i) \left\{p(E) + p'(E) \left[\omega_i - e_i(E)\right]\right\} = (1 + \theta_i d_i) D_i'(E) \ , \qquad (2.A.14)$$

which implies that $\{p(E) + p'(E) [\omega_i - e_i(E)]\} > 0$. Furthermore:

$$p(E) + p'(E)\Big[\omega_i - e_i(E)\Big] - D_i'(E) \lesseqgtr 0 \quad \Leftrightarrow \quad b_i \gtreqless d_i \ . \qquad (2.A.15)$$

Re-writing the first-order condition again yields:

$$-\frac{1}{\theta_i} \left\{p(E) + p'(E) \left[\omega_i - e_i(E)\right] - D_i'(E)\right\} = b_i \left\{p(E) + p'(E) \left[\omega_i - e_i(E)\right]\right\} - d_i D_i'(E) \ . \qquad (2.A.16)$$

Then, $b_i \{p(E) + p'(E) [\omega_i - e_i(E)]\} - d_i D_i'(E) \gtreqless 0 \quad \Leftrightarrow \quad b_i \gtreqless d_i$.

For $r_i = d_i$, the signs of equations (2.A.13a) and (2.A.13c) can be found by re-writing the first-order condition as follows:

$$(1 + \theta_i d_i) \left[p(E) + p'(E)\omega_i - D_i'(E)\right] = (1 + \theta_i b_i) p'(E) e_i(E) \ , \qquad (2.A.17)$$

which implies that $[p(E) + p'(E)\omega_i - D_i'(E)] < 0$. Furthermore:

$$p(E) + p'(E)\omega_i - D_i'(E) - p'(E)e_i(E) \gtreqless 0 \quad \Leftrightarrow \quad b_i \lesseqgtr d_i \ . \qquad (2.A.18)$$

Re-writing the first-order condition again yields:

$$-\frac{1}{\theta_i} \left[p(E) + p'(E)\omega_i - D_i'(E) - p'(E)e_i(E)\right] \\ = d_i \left[p(E) + p'(E)\omega_i - D_i'(E)\right] - b_i p'(E) e_i(E) \ . \qquad (2.A.19)$$

Then, $d_i [p(E) + p'(E)\omega_i - D_i'(E)] - b_i p'(E)e_i(E) \gtreqless 0 \quad \Leftrightarrow \quad b_i \lesseqgtr d_i$.

Inserting equations (2.A.13) into equations (2.A.11) yields Corollary 2.2. □

Proof of Proposition 2.3

Assuming that $C_{ij}^{2,R} > 0$ for all $j = 1, \ldots, M_i$ and both R, we can re-write equation

(2.23) by virtue of condition (2.10) to yield:

$$W_i^R(\omega_1^R, \omega_2^R) + \theta_i \sum_{\substack{j=1 \\ j \neq k}}^{M_i} U_{ij}^R(\omega_1^R, \omega_2^R) + \theta_i \left[U_{ik}^R(\omega_1^R, \omega_2^R) - \bar{U}_{ik}^R \right] = W_i^R(\omega_1^{-k}, \omega_2^{-k}) + \theta_i \sum_{\substack{j=1 \\ j \neq k}}^{M_i} U_{ij}^R(\omega_1^{-k}, \omega_2^{-k}) \ , \tag{2.A.20}$$

Solving for $\bar{U}_{ik}^R$ and inserting into condition (2.10), we obtain:

$$C_{ik}^{2,R}(\omega_1^R, \omega_2^R) = \frac{1}{\theta_i} \left[W_i^R(\omega_1^{-k}, \omega_2^{-k}) - W_i^R(\omega_1^R, \omega_2^R) \right] + \sum_{\substack{j=1 \\ j \neq k}}^{M_i} \left[U_{ij}^R(\omega_1^{-k}, \omega_2^{-k}) - U_{ij}^R(\omega_1^R, \omega_2^R) \right] \ . \tag{2.A.21}$$

Inserting the lobby's utility function (2.3) yields equation (2.24). □

Proof of Proposition 2.4

Condition (2.29) is a necessary condition for a pressured stance. We can re-write this condition to yield

$$G_{i0}^R + \theta_i \sum_{j \in S_R} \Delta U_{ij}^{R,\bar{R}} > G_{i0}^{\bar{R}} + \theta_i \sum_{j \in S_{\bar{R}}} \Delta U_{ij}^{\bar{R},R} \ , \tag{2.A.22a}$$

$$\Leftrightarrow \quad W_i^R + \theta_i \sum_{j=1}^{M_i} C_{ij}^{2,R} + \theta_i \sum_{j \in S_R} \left[U_{ij}^R - C_{ij}^{2,R} - U_{ij}^{\bar{R}} + C_{ij}^{2,\bar{R}} \right] > W_i^{\bar{R}} + \theta_i \sum_{j=1}^{M_i} C_{ij}^{2,\bar{R}} + \theta_i \sum_{j \in S_{\bar{R}}} \left[U_{ij}^{\bar{R}} - C_{ij}^{2,\bar{R}} - U_{ij}^R + C_{ij}^{2,R} \right] \tag{2.A.22b}$$

$$\Leftrightarrow \quad W_i^R + \theta_i \sum_{j=1}^{M_i} C_{ij}^{2,R} + \theta_i \sum_{j=1}^{M_i} \left[U_{ij}^R - C_{ij}^{2,R} \right] > W_i^{\bar{R}} + \theta_i \sum_{j=1}^{M_i} C_{ij}^{2,\bar{R}} + \theta_i \sum_{j=1}^{M_i} \left[U_{ij}^{\bar{R}} - C_{ij}^{2,\bar{R}} \right] \tag{2.A.22c}$$

$$\Leftrightarrow \quad W_i^R + \theta_i \sum_{j=1}^{M_i} U_{ij}^R > W_i^{\bar{R}} + \theta_i \sum_{j=1}^{M_i} U_{ij}^{\bar{R}} \ . \tag{2.A.22d}$$

Obviously, this condition does not depend on the distribution of organized stakes, as welfare and the sum of the lobby groups' (gross) utilities are determined by the aggregate level of organized stakes b_i, d_i and r_i. This implies that whenever there exists a pressured stance – no matter what the distribution of organized stakes among the individual lobby groups – the pressured stance supports regime R. However, whether a pressured stance exists or not may well depend on the distribution, as condition (2.30), which also has to hold for the existence of a pressured stance, is not immune to change in the distribution of organized stakes. □

Proof of Proposition 2.5

To prove the proposition, we focus on $r_i = b_i$ and introduce the special case of quadratic benefit functions and linear environmental damages:

$$B_i(e_i) = \frac{1}{\phi_i} e_i (1 - \frac{1}{2} e_i) \ , \qquad B_i'(e_i) = \frac{1}{\phi_i}(1 - e_i) \ , \qquad B_i''(e_i) = -\frac{1}{\phi_i} \ , \tag{2.A.23a}$$

$$D_i(E) = \epsilon_i E \ , \qquad D_i'(E) = \epsilon_i \ , \qquad D_i''(E) = 0 \ , \tag{2.A.23b}$$

where $\phi_i > 0$ denotes a country-specific benefit parameter, and $\epsilon_i > 0$ is country-specific but constant marginal damage. We define the following shortcuts for politically adjusted marginal damages, average politically adjusted marginal damages and the average benefit parameter:

$$\psi_i = \tilde{D}_i'(E) = \frac{1 + \theta_i d_i}{1 + \theta_i b_i} \epsilon_i \ , \qquad \bar{\psi} = \frac{1}{2}(\psi_i + \psi_{-i}) \ , \qquad \bar{\phi} = \frac{1}{2}(\phi_i + \phi_{-i}) \ . \tag{2.A.24}$$

Then, the national allowance choices and the global emissions in the two regimes are:

$$E^I = 2 - \bar{\phi}(\psi_i + \psi_{-i}) \ , \qquad E^D = 2 - (\phi_i \psi_i + \phi_{-i}\psi_{-i}) \ , \tag{2.A.25a}$$

$$e_i^I = 1 - \phi_i \bar{\psi} \ , \qquad e_i^D = 1 - \phi_i \psi_i \ , \tag{2.A.25b}$$

$$\omega_i^I = 1 + \phi_{-i}\bar{\psi} - 2\bar{\phi}\psi_i \ . \tag{2.A.25c}$$

Global emissions are lower in case of linking the domestic permit market to an international permit market if the country with the higher ϕ_i exhibits the lower politically adjusted marginal damages ψ_i:

$$E^I \gtreqless E^D \qquad \Leftrightarrow \qquad \phi_{-i}(\psi_{-i} - \psi_i) \gtreqless \phi_i(\psi_{-i} - \psi_i) \ . \tag{2.A.26}$$

Equation (2.32) can be written as:

$$\Delta G_i = (1 + \theta_i b_i) \left\{ B_i\Big(e_i(E^I)\Big) - B_i(e_i^D) + p(E^I)\left[\omega_i^I - e_i(E^I)\right]\right\} \\ - (1 + \theta_i d_i)\left[D_i(E^I) - D_i(E^D)\right] + \theta_i(r_i - b_i)\left[p(E^I)\omega_i^I - p_i(\omega_i^D)\omega_i^D\right] > 0 \ , \tag{2.A.27}$$

where the last term cancels out for $r_i = b_i$. Factoring out $(1+\theta_i b_i)$ before differentiating equation (2.A.27) and defining $\gamma_i \equiv (1+\theta_i d_i)/(1+\theta_i b_i)$, we derive:

$$\frac{d\Delta G_i}{dx_i} = \frac{d(1+\theta_i b_i)}{dx_i}\frac{\Delta G_i}{1+\theta_i b_i} + (1+\theta_i b_i)\left[\epsilon_i \frac{d\gamma_i}{dx_i}(E^D - E^I) - \epsilon_i \frac{d\gamma_i}{dx_i}\frac{1}{2}\phi_i\bar{\psi}\right] \quad \text{(2.A.28a)}$$

$$= \frac{d(1+\theta_i b_i)}{dx_i}\frac{\Delta G_i}{1+\theta_i b_i} + (1+\theta_i b_i)\epsilon_i \frac{d\gamma_i}{dx_i}\left[(\bar{\phi}-\phi_i)\psi_i + (\bar{\phi}-\phi_{-i})\psi_{-i} - \frac{1}{2}\phi_i\bar{\psi}\right] ,$$

$$\frac{d\Delta G_{-i}}{dx_i} = (1+\theta_{-i}b_{-i})\epsilon_i \frac{d\gamma_i}{dx_i}\left[\omega^I_{-i} - e^D_{-i} + \frac{1}{2}\phi_{-i}\bar{\psi}\right] \quad \text{(2.A.28b)}$$

$$= (1+\theta_{-i}b_{-i})\epsilon_i \frac{d\gamma^I_i}{dx_i}\left[\phi_i(\bar{\psi} - \psi_{-i}) + \frac{1}{2}\phi_{-i}\bar{\psi}\right] ,$$

where $x \in \{\theta, b, d, r\}$ and

$$\frac{d\gamma_i}{d\,b_i} = -\frac{\theta_i(1+\theta_i d_i)}{(1+\theta_i b_i)^2} < 0 \ , \frac{d\gamma_i}{d\,d_i} = \frac{\theta_i}{1+\theta_i b_i} > 0 \ , \frac{d\gamma_i}{d\,\theta_i} = \frac{d_i - b_i}{(1+\theta_i b_i)^2} \gtreqless 0 \Leftrightarrow d_i \gtreqless b_i \ . \quad \text{(2.A.29)}$$

Consider the situation of an established international permit market with $E^D > E^I$. Now, assume, for example, that the green lobby in country i gains momentum (i.e. d_i increases). Then, the first term in equation (2.A.28a) drops out. The direct effect goes into the direction of the regime with lower emissions, which is the international trade regime. However, the indirect effect of country i goes in favor of the domestic regime and may even outweigh the direct effect. As a consequence, the government in country i is less in favor of the international regime than before. Also the indirect effect in country $-i$ may induce the government of country $-i$ to support the international permit trading regime less than before. Thus, the gain in influence of the green lobby in country i may cause the support for this regime to cease in one or both of the countries. As a consequence, the regime changes to the other regime. As (by assumption) the domestic trading regime exhibits higher global emissions than the international trading regime, global emissions rise which is counter to the interests of the green lobby group. □

Chapter 3

Mobile Capital and Non-cooperative International Environmental Policy

3.1 Introduction

One of the key questions in the literature on fiscal federalism is whether and to what extent decentralized policies are efficient. The same question features prominently in the environmental economics literature, in particular, in the case of transnational and global pollutants, such as sulfur dioxide or greenhouse gas emissions. Yet, there are substantial differences between these two strands of the literature. While the fiscal federalism literature focuses on the economic competition between individual jurisdictions over mobile factors of production, the bulk of the theoretical environmental literature is concerned with trading off the costs and benefits of emissions which cause transnational or global pollution damages. At the intersections of these two literature strands is the literature on "environmental dumping" which considers the competition for mobile factors that give rise to interjurisdictional spillovers. So far, however, this literature produced inconclusive results. While some papers find that decentralized policy-making is efficient (e.g. Oates and Schwab, 1988; Ogawa and Wildasin, 2009), others find that the resulting pollution levels are inefficiently high (e.g. Eichner and Runkel, 2012) or may even be inefficiently low (e.g. Rauscher, 1991; Withagen and Halsema, 2013).

In this paper, we structure this debate by analyzing the interactions of mobile capital and non-cooperative international environmental policy under different sets of assumptions. We compare the cases when capital and emissions are either perfect complements or perfect substitutes. Like Eichner and Runkel (2012), we allow for an endogenous choice of capital and emissions and stick to the case of symmetric countries. In addition, we account for the possibility that interjurisdictional spillovers do not only impact on the households' utility but may also negatively affect production. This allows for the important distinction between non-market (utility) and market (production) damages from pollution. We model the pollution externality on production as a negative impact of higher pollution on the marginal productivity of capital.

In case of perfect complementarity between capital and emissions, capital taxes (which are equivalent to taxes on emissions) are inefficiently low in the symmetric Nash equilibrium for a positive capital supply elasticity but set at a strictly positive rate. Even though a unilateral increase of the capital tax lowers pollution and thus increases capital demand in the tax-increasing country through its positive impact on the marginal productivity of capital, the tax increase does not attract investment. This is because investment cannot rise when pollution falls due to their complementary relationship.

If capital and emissions are perfect substitutes, they may be addressed separately by policy-makers through a tax on capital *and* a tax on emissions. We show that an increase in the emissions tax and a decrease in the capital tax have the same quantitative effects on global capital use by firms and global pollution. Thus, capital and pollution depend only on the difference in emissions and capital taxes. In the Nash equilibrium, governments may subsidize capital and/or emissions, depending on the size of pollution impacts on production.

In contrast to the model with perfect complementarity, a unilateral marginal increase in the tax difference, caused by either an increase of the emissions tax or a decrease in the capital tax, may indeed attract capital *and* lower pollution at the same time. This holds for sufficiently strong pollution impacts on production and incentivizes governments to set an inefficiently high tax difference in equilibrium. We also show that a binding international agreement setting the emissions tax rate equal to the social marginal damage from emissions would eliminate all incentives for capital tax competition.

Our paper contributes to the literature on environmental policy and interjurisdictional competition in the spirit of Zodrow and Mieszkowski (1986). In their pioneering article Oates and Schwab (1988) show – in a setting of symmetric countries, perfect complementarity between capital and emissions, and environmental externalities that do not spill over to other jurisdictions – that decentralized policy-making is efficient if internal efficiency within each jurisdiction is guaranteed (for example, by lump-sum taxes). Ogawa and Wildasin (2009) extend this efficiency result to the case of interjurisdictional spillovers and asymmetric countries. This surprising finding stems from the fact that two externalities, a fiscal externality due to the tax competition incentive of governments and the environmental externality, exactly offset each other in equilibrium. It rests, however, on the strong assumption that global capital supply is fixed, which implies that global emissions are exogenously given due to the perfect complementarity between capital and emissions. Eichner and Runkel (2012), henceforth E&R, employ a similar model that keeps the complementarity assumption but allows for endogenous capital supply. They show that the tax on capital is inefficiently low in the decentralized equilibrium. The reason is that, although a unilateral increase in the capital tax attracts capital, it also lowers global capital demand and leads to a fall in the interest rate. For a positive capital supply elasticity, this implies lower savings and, therefore, lower capital and emissions in all other countries. This effect decreases the environmental externality compared to a regime with fixed capital supply such that the environmental externality is not strong enough any more to offset the distortion due to the fiscal externality. In this paper, we amend the model of E&R by pollution externalities on production and also analyze a model variant with perfect substitutability between capital and emissions.

The paper is also related to Rauscher (1991, 1997b,a, 2000, 2005) who finds, using similar models of decentralized environmental policy-making and mostly heterogeneous countries, that capital mobility may aggravate transfrontier pollution problems whenever capital and emissions are somewhat complementary. Only with sufficiently strong emission externalities on the marginal productivity of capital and a low degree of substitutability may environmental standards become inefficiently strict (Rauscher 1997b,a). In a world with identical countries, governments are found to internalize even less than their own shares of the environmental externality (Rauscher 2005). In contrast to the models employed by Rauscher, our model allows for endogenous capital supply.

The remainder of the paper is structured as follows. In Section 3.2, we analyze a model similar to E&R amended by pollution externalities on production. In Section 3.3, we assume that capital and emissions are perfect substitutes. To be able to compare the results with the previous section, we do this by changing the model as little as possible. We discuss our results for two important special cases in Section 3.4. Finally, Section 3.5 concludes.

3.2 The model with production externalities

In a first step, we discuss a model where the main difference to the model employed by E&R is that we allow for pollution externalities on production. We consider a model of a global economy consisting of $n \geq 2$ symmetric jurisdictions which can be thought of as sovereign countries.

3.2.1 Firms, emissions and pollution

In each country, a representative firm produces an output good, the price of which we normalize to one. Firms in all countries have access to the same production technology F, which is increasing in the amount of a production factor k_i (that we call 'capital') with decreasing marginal returns ($F_{kk} < 0 < F_k$). Capital is traded on a global capital market at the uniform price ρ.

Each unit of capital k_i gives rise to emissions that increase the pollution level by $\alpha > 0$ units in country i and by $\alpha\beta$ ($\beta \in [0, 1]$) units in all other countries $j \neq i$. Thus, the parameter β specifies the magnitude of transboundary emission spillovers. For $\beta = 0$ emissions only cause *local* pollution, i.e. their effect is confined to the country of origin, while for $\beta = 1$ emissions cause *global* pollution in the sense that all jurisdictions are equally affected by an increase in k_i. Thus, the pollution level e_i in country i amounts to:

$$e_i = \alpha\Big(k_i + \beta \sum_{j \neq i} k_j\Big) \ . \tag{3.1}$$

In contrast to E&R, we assume that pollution negatively affects production. In particular, the level of output is lower, the higher is the pollution level e_i ($F_e < 0$). Furthermore, the marginal productivity of capital (MPC) is weakly decreasing in e_i, i.e. $F_{ke} \leq 0$.[1]

Given that country i levies a unit source-based tax t_i on capital and that the produced consumption good is sold on a perfectly competitive global market, after-tax profits of the representative firm in country i are given by:

$$\pi_i = F(k_i, e_i) - (\rho + t_i)k_i \ . \tag{3.2}$$

Taking the pollution level e_i as given, profit maximization of the representative firms implies that after-tax returns to capital are equalized across countries:

$$F_k(k_i, e_i) - t_i = \rho \ . \tag{3.3}$$

3.2.2 Households

Each country is populated by a representative household endowed with $\bar{k}$ units of capital. Capital can either be directly consumed (x_i^1) or provided to a global capital market in amount $s_i = \bar{k} - x_i^1$. We assume that households own the representative firm in their country of origin and the government re-distributes the revenues from the capital tax via a lump-sum transfer:[2]

$$\tau_i = t_i k_i \ . \tag{3.4}$$

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[1] Pollution damages that negatively impact on the marginal productivity of capital can be found, among others, in Baumol and Bradford (1972), Rauscher (1997b,a), Copeland and Taylor (1999) and Benarroch and Thille (2001). An alternative interpretation is that lower emission levels, i.e. higher emission abatement, is a local public input to production. On public input competition see, e.g., Noiset (1995), Keen and Marchand (1997), Sinn (1997), Matsumoto (1998), Bayindir-Upmann (1998) and Dhillon et al. (2007).

[2] If the government in country i wants to subsidize capital then τ_i becomes a lump-sum tax. In particular, we abstract from taxing capital to provide local public goods. As we assume that the government can raise a lump-sum tax, local public good provision is trivial.

Then, the budget for the produced good x_i^2 (which is equal to its consumption, as the price of the good is normalized to one) is given by:

$$x_i^2 = \rho s_i + \pi_i + \tau_i \ . \tag{3.5}$$

The household receives utility from consuming x_i^1 and x_i^2 but is harmed by pollution e_i. The utility function is quasi-linear in consumption and additively separable in consumption and pollution:[3]

$$W_i = U(x_i^1) + x_i^2 + V(e_i) = U(\bar{k} - s_i) + \rho s_i + \pi_i + \tau_i + V(e_i) \ , \tag{3.6}$$

where U is monotonically increasing, V is monotonically decreasing and both functions are concave.

The model allows for two different interpretations. First, x_i^1 and x_i^2 may be interpreted as first and second stage consumption. In this case, we obtain an intertemporal model in which s_i denotes savings that earn interest at a rate of $\rho - 1$. Second, the model may be interpreted as a static model in which x_i^1 and x_i^2 denote the consumption of two different commodities, where the first commodity can be either consumed or used as an input in production. Then, s_i denotes the amount of the first commodity which is sold to the firms at the price ρ. While E&R phrase their model in the spirit of the former interpretation, we prefer the latter. In both cases the consumption good x_i^1 serves as a parsimonious way to endogenize capital supply.

Households choose capital supply s_i to maximize utility (3.6), taking firm profits and the pollution level as given. From the necessary and sufficient condition for a household maximum,

$$U'(\bar{k} - s_i) - \rho = 0 \ , \tag{3.7}$$

we obtain that a marginal increase in the price of capital ρ increases capital supply and thus decreases consumption x_i^1:

$$\frac{\partial s_i}{\partial \rho} = s_i' = -\frac{1}{U''(\bar{k} - s_i)} > 0 \ . \tag{3.8}$$

[3] Quasi-linearity neglects any income effects and can be justified on the grounds that there is empirical evidence that the substitution effect outweighs the income effect (see, for example, Boskin, 1978, or Gylfason, 1993).

3.2.3 Global capital market

Capital is perfectly mobile across countries and traded on a global capital market. The equilibrium condition is given by:

$$\sum_{l=1}^{n} k_l(\rho, t_l) = \sum_{l=1}^{n} s_l(\rho) \ . \tag{3.9}$$

Equations (3.1), (3.3), (3.7) and (3.9) determine the price of capital ρ as well as the equilibrium levels of capital and pollution in all countries as a function of the capital tax rates in all countries. We obtain the comparative static results with respect to a marginal change in country i's tax rate by taking the total derivative of these equations. For a symmetric equilibrium ($k_i = s_i = S$), it holds (for the explicit derivations see the Appendix):

$$\frac{d\rho}{dt_i} = -\frac{1}{n(1-\Phi-\Gamma)} < 0 \ , \tag{3.10}$$

$$\frac{dk_i}{dt_i} = \frac{S'\Big[(n-1) - n(\Phi+\Gamma-\beta\Gamma_i)\Big]}{n(1-\Phi-\Gamma)\Big[\Phi+(1-\beta)\Gamma_i\Big]} < 0 \ , \tag{3.11a}$$

$$\frac{dk_j}{dt_i} = -\frac{S'(1-n\beta\Gamma_i)}{n(1-\Phi-\Gamma)\Big[\Phi+(1-\beta)\Gamma_i\Big]} > 0 \ , \tag{3.11b}$$

$$\frac{dk}{dt_i} = \frac{dk_i}{dt_i} + (n-1)\frac{dk_j}{dt_i} = -\frac{S'}{1-\Phi-\Gamma} < 0 \ , \tag{3.11c}$$

where $\Phi = F_{kk}S' < 0$, $\Gamma_i = \alpha F_{ke}S' < 0$ and $\Gamma = [1+(n-1)\beta]\Gamma_i < 0$. The pollution externality on production is thus represented by the terms Γ_i and Γ. Qualitatively, these additional terms do not change the results compared to E&R for marginal changes in the capital tax t_i. A marginal increase in the capital tax t_i decreases capital use in the tax-increasing country and increases capital use in all other countries, yet the global effect is negative. In the market equilibrium of the capital market, this reduction in global capital use is supported by a decreasing price of capital.

Due to perfect complementarity, a marginal change in the capital tax t_i also affects the pollution levels in all countries:

$$\frac{de_i}{dt_i} = \frac{\alpha S'\Big[(1-\beta)\Big(n-1-n\Gamma\Big) - n\Phi\Big]}{n(1-\Phi-\Gamma)\Big[\Phi+(1-\beta)\Gamma_i\Big]} < 0 \ , \tag{3.12a}$$

$$\frac{de_j}{dt_i} = -\frac{\alpha S' \Big[(1-\beta) + n\beta\Phi)}{n(1-\Phi-\Gamma)\Big[\Phi + (1-\beta)\Gamma_i\Big]} \gtreqless 0 \;, \tag{3.12b}$$

$$\frac{de}{dt_i} = \frac{de_i}{dt_i} + (n-1)\frac{de_j}{dt_i} = \frac{-\alpha S' \Big[1 + (n-1)\beta\Big]}{1-\Phi-\Gamma} < 0 \;. \tag{3.12c}$$

As an increase in the capital tax in country i decreases domestic and global capital use, the pollution levels in country i and in aggregate decline. The effect on the pollution levels in all other countries $j \neq i$ is ambiguous because of two opposing effects. On the one hand, investment in these countries increases and, accordingly, local emissions and pollution levels rise. On the other hand, the decline in emissions in the tax-increasing country i reduces emission spillovers to country j. Which of the two effects prevails, depends on the spillover parameter β. For a sufficiently high β, pollution levels in all other countries $j \neq i$ fall as well. The beneficial effect of a tax increase on the domestic pollution level offsets even potential increases in pollution levels in other countries such that aggregate pollution falls.

Like in E&R, a unilateral increase in the capital tax t_i unambiguously repels capital and lowers local pollution levels. Even though this decrease goes along with an increase in domestic capital demand, ceteris paribus, due to the pollution externality on the MPC, governments are not able to increase domestic investment by increasing capital taxes. As we shall see in the following section, governments strike a balance between the opposing effects on investment and local pollution by lowering capital taxes below their efficient level.

3.2.4 Decentralized equilibrium

The governments in all countries i simultaneously choose a capital tax t_i to maximize the utility of its representative household (3.6) subject to (3.2), (3.3), (3.4), (3.8), (3.10), (3.11a), (3.12a), taking the tax rates in all other countries as given. Assuming that an interior symmetric Nash equilibrium exists, the symmetric equilibrium tax rate reads:

$$\hat{t} = -\alpha(F_e + V_e)\frac{(n-1)(1-\beta) - n(\Phi + \Gamma - \beta\Gamma_i)}{(n-1) - n(\Phi + \Gamma - \beta\Gamma_i)} > 0 \;. \tag{3.13}$$

The equilibrium capital tax rate $\hat{t}$ is positive and a function of the environmental damage imposed on own utility and own production.

The tax rate in the symmetric Nash equilibrium is, in general, inefficient. To see this, recall first that for symmetric countries efficiency requires for $i \neq j$:

$$\frac{\partial W_i}{\partial t_i} + (n-1)\frac{\partial W_j}{\partial t_i} = 0 \ , \qquad \forall\, i = 1, \ldots, n \ , \tag{3.14a}$$

which implies:

$$t_i \frac{\partial k}{\partial t_i} = -(F_e + V_e)\frac{\partial e}{\partial t_i} \ . \tag{3.14b}$$

For $S' = 0$, as in Ogawa and Wildasin (2009), $\partial k/\partial t_i = \partial e/\partial t_i = 0$ implying that condition (3.14b) holds for all tax rates, including the tax rate in the symmetric Nash equilibrium.

Second, for elastic capital supply, i.e. $S' > 0$, we obtain from condition (3.14b) by using equations (3.11b) and (3.12b):

$$t^{\star} = -\alpha(F_e + V_e)[1 + (n-1)\beta] \ , \tag{3.15}$$

implying that the Pareto efficient tax rate equals the social marginal damage (SMD) from emissions.

We cannot easily compare the tax rates in the symmetric Nash equilibrium and in the Pareto optimum, as environmental damage depends on emissions and, in particular, on the capital stock. Emissions and capital, in turn, differ in the Nash equilibrium and in the Pareto optimum. To see that the tax rate in the Nash equilibrium is inefficient, we analyze whether a marginal increase of the tax rate in the symmetric Nash equilibrium constitutes a Pareto improvement. By construction, $\partial W_i/\partial t_i = 0$ in the symmetric Nash equilibrium, thus a unilateral marginal tax increase is a Pareto improvement if $\partial W_j/\partial t_i > 0$, i.e. if it raises the welfare in all other countries while it leaves the welfare in the tax increasing country unchanged. If this is the case, then the tax rate in the symmetric Nash equilibrium is inefficiently low. As in E&R, the policy externalities from a unilateral tax increase can be decomposed into a private income and an environmental externality:

$$\frac{\partial W_j}{\partial t_i} = \underbrace{\hat{t}\frac{dk_j}{dt_i}}_{\text{IE>0}} + \underbrace{(F_e + V_e)\frac{de_j}{dt_i}}_{\text{EE}} \ . \tag{3.16}$$

The private income externality (IE) is unambiguously positive, indicating inefficiently low tax rates whereas the environmental externality (EE) cannot be signed unambiguously. Inserting the equilibrium tax rate $\hat{t}$ from (3.13) and the comparative statics

(3.11b) and (3.12b), we obtain:

$$\frac{\partial W_j}{\partial t_i} = -\alpha\beta S'(F_e + V_e)\frac{n(1-\Phi-\Gamma)[\Phi+(1-\beta)\Gamma_i]+(n-1)\beta\Gamma_i(1-n\beta\Gamma_i)}{(1-\Phi-\Gamma)[\Phi+(1-\beta)\Gamma_i][n-1-n(\Phi+\Gamma-\beta\Gamma_i)]} > 0 \ . \tag{3.17}$$

This leads us to the following proposition that is in line with E&R and constitutes the standard result in the tax competition literature (Zodrow and Mieszkowski, 1986).

Proposition 3.1 (Inefficiently low tax rate under perfect complementarity) *In the E&R model amended by production externalities, the tax rate $\hat{t}$ in the symmetric Nash equilibrium is inefficiently low if $S' > 0$.*

Thus, in case of perfect complementarity between capital and emissions, the pollution externalities on production do not qualitatively change results. In any case, equilibrium taxes on capital are inefficiently low. We shall see in the following section that pollution externalities on production play a more important role if capital and emissions are perfect substitutes.

3.3 The model with capital and emissions as perfect substitutes

The model in the previous section assumes, like its predecessors in Oates and Schwab (1988), Ogawa and Wildasin (2009) and E&R, that capital and emissions are perfect complements. Exemplarily, we may think of electricity production in conventional coal- or gas-fired power plants, where the relationship between resource input and emissions is governed by the combustion process. From a macroeconomic perspective this rigid relationship does not always hold. In fact, the opposite may be true if we consider, for example, investments in renewable energies. To highlight the effects of perfect complementarity, we now assume the opposite, i.e. capital and emissions are perfect substitutes.

3.3.1 Assumptions

We achieve this in the most parsimonious way by assuming that not capital use in the production of the second good but the consumption of the first good causes the environmental externality:

$$e_i = \alpha\Big(x_i^1 + \beta\sum_{j\neq i} x_j^1\Big) \ . \tag{3.18}$$

That is, the higher is the consumption of the first good in country i, the higher are domestic emissions which partly or fully spill over to other countries, but also the less capital can be sold to firms. This indicates the substitutive relationship between capital and emissions. Like in the previous model specification, emissions negatively affect production and households' utility.

As the pollution externality is now caused by the consumption of good x_i^1, the government in country i may levy an additional consumption (respectively emissions or environmental) tax ϵ_i. Then the consumption of the second good is given by:

$$x_i^2 = \rho s_i + \pi_i + \tau_i - \epsilon_i(\bar{k} - s_i) \ , \tag{3.19}$$

where

$$\tau_i = t_i k_i + \epsilon_i(\bar{k} - s_i) \tag{3.20}$$

denotes the lump-sum tax/transfer that balances the government's budget. The household's utility is given by:

$$W_i = U(\bar{k} - s_i) + \rho s_i + \pi_i + \tau_i - \epsilon_i(\bar{k} - s_i) + V(e_i) \ , \tag{3.21}$$

and the first-order condition for the household's maximum yields:

$$U'(\bar{k} - s_i) - \rho - \epsilon_i = 0 \ . \tag{3.22}$$

Thus, a marginal increase in the consumption tax ϵ_i has the same effect on capital supply as a marginal increase of the price of capital ρ:

$$\frac{\partial s_i}{\partial \epsilon_i} = \frac{\partial s_i}{\partial \rho} = s_i' = -\frac{1}{U''(\bar{k} - s_i)} > 0 \ . \tag{3.23}$$

3.3.2 Comparative statics

With capital supply in country i being a function of ρ and ϵ_i, the capital market equilibrium is determined by the following condition:

$$\sum_{l=1}^{n} k_l(\rho, t_l) = \sum_{l=1}^{n} s_l(\rho, \epsilon_l) \ . \tag{3.24}$$

Using equations (3.3), (3.18) and (3.24) and assuming a symmetric equilibrium, we obtain the comparative static results of marginal changes in country i's tax rates t_i

(left-hand side) and ϵ_i (right-hand side), which are derived in detail in the Appendix:

$$\frac{d\rho}{dt_i} = -\frac{1}{n(1-\Phi+\Gamma)}\ , \quad \frac{d\rho}{d\epsilon_i} = \frac{\Phi-\Gamma}{n(1-\Phi+\Gamma)}\ , \tag{3.25}$$

$$\frac{dk_i}{dt_i} = \frac{S'\Big[(n-1)(1+\Gamma)-n\Phi\Big]}{n\Phi(1-\Phi+\Gamma)}\ , \quad \frac{dk_i}{d\epsilon_i} = \frac{S'\Big[(n-1)(1-\beta)\Gamma_i(1-\Phi+\Gamma)+\Phi\Big]}{n\Phi(1-\Phi+\Gamma)}\ , \tag{3.26a}$$

$$\frac{dk_j}{dt_i} = -\frac{S'(1+\Gamma)}{n\Phi(1-\Phi+\Gamma)}\ , \qquad \frac{dk_j}{d\epsilon_i} = -\frac{S'\Big[(1-\beta)\Gamma_i(1-\Phi+\Gamma)-\Phi\Big]}{n\Phi(1-\Phi+\Gamma)}, \tag{3.26b}$$

$$\frac{dk}{dt_i} = -\frac{S'}{1-\Phi+\Gamma}\ , \qquad \frac{dk}{d\epsilon_i} = \frac{S'}{1-\Phi+\Gamma}\ , \tag{3.26c}$$

$$\frac{de_i}{dt_i} = \frac{\alpha S'\Big[1+(n-1)\beta\Big]}{n(1-\Phi+\Gamma)}\ , \qquad \frac{de_i}{d\epsilon_i} = -\frac{\alpha S'\Big[n+(n-1)(1-\beta)(\Gamma-\Phi)\Big]}{n(1-\Phi+\Gamma)}\ , \tag{3.27a}$$

$$\frac{de_j}{dt_i} = \frac{\alpha S'\Big[1+(n-1)\beta\Big]}{n(1-\Phi+\Gamma)}\ , \qquad \frac{de_j}{d\epsilon_i} = -\frac{\alpha S'\Big[\beta n-(1-\beta)(\Gamma-\Phi)\Big]}{n(1-\Phi+\Gamma)}\ , \tag{3.27b}$$

$$\frac{de}{dt_i} = \frac{\alpha S'\Big[1+(n-1)\beta\Big]}{1-\Phi+\Gamma}\ , \qquad \frac{de}{d\epsilon_i} = -\frac{\alpha S'\Big[1+(n-1)\beta\Big]}{1-\Phi+\Gamma}\ . \tag{3.27c}$$

Compared to the case of perfect complementarity, Γ enters the denominator in all equations with a positive sign instead of a negative one. The signs of all comparative static results now depend on the environmental spillover parameter β and in particular on the size of Γ and/or Γ_i and thus on the size of F_{ke}. It is straightforward to see that if there are no externalities from pollution on production, i.e. $F_{ke} = 0$ and thus $\Gamma = \Gamma_i = 0$, a marginal change in t_i has the same effects as before on the capital market related variables ρ, k_i, k_j and k but opposing effects on domestic and aggregate pollution e_i and e due to perfect substitutability.

For sufficiently small pollution impacts on the MPC, i.e. if F_{ke} is not too negative such that $-\Gamma < 1-\Phi$, these results still hold qualitatively. However, if the pollution externality on production is sufficiently large, these results are reversed. A marginal increase in t_i then increases the equilibrium price of capital because the increase of aggregate capital demand associated with the decrease in pollution due to $F_{ke} < 0$ outweighs the direct negative effect of the tax increase on aggregate investment. For the knife-edge case of $-\Gamma = 1-\Phi$, both effects exactly offset each other such that the price of capital and thus investment and pollution levels are insensitive to a marginal change in t_i.

A marginal increase in ϵ_i affects the price of capital via two channels. First, it changes emissions directly by changing consumption of the externality-generating first good in country i. This change is, on the one hand, associated with a ceteris paribus increase in capital supply by country i and, thus, *aggregate capital supply* increases. On the other hand, the decrease in emissions in country i due to an increase in ϵ_i also decreases the pollution levels in all countries, which increases the demand for capital everywhere due to the pollution externality on production ($F_{ke} < 0$). Accordingly, also *aggregate capital demand* increases. The effect on the price of capital is thus ambiguous. Second, there is an indirect effect via the global capital market which is also ambiguous. The reason is that, for instance, a marginal increase in the price of capital raises, ceteris paribus, capital demand due to the pollution externality on production and thus counteracts the dampening effect of an increase in ρ on investment. The combined effect of these two channels on the price of capital is ambiguous, depending on the strength of the pollution externality on production. In fact, ρ rises for $-\Phi < -\Gamma < 1 - \Phi$ and falls otherwise. Again, for $-\Gamma = 1 - \Phi$, the price of capital and all other variables are perfectly inelastic to marginal tax changes.

To gain a better understanding of the effects at work, we separate the different channels through which the increase in t_i or ϵ_i affects investment and pollution in the tax-increasing country. For this purpose, we take the total derivative of equations (3.3) and (3.18):

$$dk_i = \frac{1}{F_{kk}}\Big(dt_i + d\rho - F_{ke}de_i\Big) \ , \tag{3.28a}$$

$$de_i = -\alpha\left[\Big(s_i' + \beta\sum_{j\neq i} s_j'\Big)d\rho + s_i' d\epsilon_i\right] \ . \tag{3.28b}$$

A unilateral increase in the capital tax has a direct negative effect on domestic investment (first term in brackets in equation (3.28a)), but also two ambiguous effects through the associated impact on the price of capital and pollution (second and third term). The impact on pollution, (3.28b), in turn, also works via the associated change in ρ: a higher price of capital, for example, decreases consumption of the externality-generating first good in all countries and thus domestic and foreign pollution levels. Therefore, due to $F_{ke} < 0$ the capital demand curve of the firm in the tax-increasing country is shifted to the right, which, ceteris paribus, increases investment.

By contrast, a marginal change in ϵ_i entails – in addition to the indirect and ambiguous effect via the impact on ρ – a direct positive effect on domestic emissions since it makes consumption x_i^1 less attractive. However, there is no direct effect on investment, only indirect and again ambiguous effects through the changes in ρ and e_i.

A marginal increase in t_i causes a capital flow into the tax-increasing country for intermediate pollution impacts, i.e. $1 - \Phi < -\Gamma < 1 - n\Phi/(n-1)$, while local pollution falls for $-\Gamma < 1 - \Phi$. For $1 - \Phi < -\Gamma < 1 - \Phi + \Phi/[(n-1)(1-\beta)\Gamma_i]$, domestic investment falls due to a marginal increase in ϵ_i, and local pollution rises for $1 - \Phi < -\Gamma < n/[(n-1)(1-\beta)] - \Phi$. Thus, for a sufficiently high pollution externality on the MPC, domestic investment can indeed be increased while pollution falls by either marginally increasing ϵ_i or decreasing t_i. This stands in contrast to the model with perfect substitutability where domestic investment and pollution always moved in the same direction for marginal tax increases.

We also observe that a marginal increase in t_i has the same quantitative effect on the global capital stock and the global pollution level as a marginal increase in ϵ_i, but the opposite sign (equations (3.26c) and (3.27c)). In this sense, these two instruments are perfect substitutes when it comes to their impact on aggregate variables. This has an important implication, as the following proposition states.

Proposition 3.2 (Equilibrium pollution levels and investment)
For given tax rates in all other countries, the equilibrium levels of pollution and capital only depend on the difference $\epsilon_i - t_i$.

The proof is given in the Appendix.

3.3.3 Decentralized equilibrium

As a benchmark to which we compare the symmetric Nash equilibrium, we determine Pareto-optimal policies. It turns out that the efficient outcome – given that $S' > 0$ – only fixes the difference between the two taxes, which again has to equal the SMD from emissions:

$$(\epsilon - t)^\star = -\alpha(F_e + V_e)\left[1 + (n-1)\beta\right] \; . \tag{3.29}$$

Given the result of Proposition 3.2, this additional degree of freedom is not surprising. A global social planner may either tax consumption of the externality-generating good or subsidize the substitute, capital, or impose any convex combination of the two.

In the decentralized economy, the governments in all countries i simultaneously choose tax rates t_i and ϵ_i to maximize the utility of their representative household (3.21) subject to (3.2), (3.3), (3.20), (3.23), (3.25), (3.26a) and (3.27a) and taking the tax rates in all other countries as given. Assuming that a symmetric Nash equilibrium with an interior solution exists, the first-order conditions yield:

$$\epsilon_i = -\alpha(F_e + V_e)\frac{1 + (1-\beta)(\Gamma - \Phi)}{1 - \Phi + \Gamma - \beta\Gamma_i}\ , \tag{3.30a}$$

$$t_i = -\left\{\epsilon_i + \alpha(F_e + V_e)[1 + (n-1)\beta]\right\}\frac{\Phi}{(n-1)(1+\Gamma) - n\Phi} \tag{3.30b}$$

$$= -\alpha(F_e + V_e)\frac{\beta\Phi}{1 - \Phi + \Gamma - \beta\Gamma_i}\ . \tag{3.30c}$$

Either of the two tax rates may be positive or negative, yet a negative capital tax and a positive consumption tax are more likely to prevail.

From equation (3.30b) we observe that the equilibrium capital tax rate depends on the level of the environmental tax rate. If, for example, the environmental tax rate were, for whatever reason, exogenously fixed to the SMD from emissions, the equilibrium capital tax rate would be zero. This observation has an important implication.

Proposition 3.3 (Efficiency through global environmental agreement)
A global environmental agreement setting the emission tax ϵ_i in all countries equal to the SMD from emissions removes all capital tax competition incentives of the governments if internal efficiency is granted.

Thus, if all countries were to agree on a binding global environmental agreement that sets the consumption tax rate to the SMD from emissions, efficiency would prevail. This is a reassuring result, as most of the literature on international environmental agreements neglects capital mobility. Proposition 3.3 states that capital mobility can indeed be neglected if the environmental externality is fully internalized by an emission tax. However, this result crucially hinges on the assumption that lump-sum taxes are available to ensure the efficient provision of local public goods. If governments need to rely on the taxation of mobile tax bases for this purpose, additional distortions arise.

According to Proposition 3.2, equilibrium pollution and capital are determined by the difference between the environmental and the capital tax $\epsilon_i - t_i$. Assuming that an interior symmetric Nash equilibrium exists, this difference in the symmetric Nash equilibrium is given by:

$$(\widehat{\epsilon - t}) = -\alpha(F_e + Ve)\frac{1 - \Phi + \Gamma - \beta\Gamma}{1 - \Phi + \Gamma - \beta\Gamma_i}\ . \tag{3.31}$$

In the extreme case, this tax difference may be even negative in the symmetric Nash equilibrium although it is, according to (3.29), positive in the Pareto optimum.

As in the previous section, we note that Pareto efficiency requires:

$$\frac{\partial W_i}{\partial t_i} + (n-1)\frac{\partial W_j}{\partial t_i} = 0 \quad \Leftrightarrow \quad t_i\frac{dk}{dt_i} + (F_e + V_e)\frac{de}{dt_i} = n\epsilon_i S'\frac{d\rho}{dt_i} \ , \tag{3.32a}$$

$$\frac{\partial W_i}{\partial \epsilon_i} + (n-1)\frac{\partial W_j}{\partial \epsilon_i} = 0 \quad \Leftrightarrow \quad t_i\frac{dk}{d\epsilon_i} + (F_e + V_e)\frac{de}{d\epsilon_i} = \epsilon_i S'\left[1 + n\frac{d\rho}{d\epsilon_i}\right] \ . \tag{3.32b}$$

Again, both conditions hold for all tax rates whenever $S' = 0$. The policy externalities for a unilateral tax increase now read:

$$\frac{\partial W_j}{\partial t_i} = t_j\frac{dk_j}{dt_i} - \epsilon_j S'\frac{d\rho}{dt_i} + (F_e + V_e)\frac{de_j}{dt_i} \ , \tag{3.33}$$

$$\frac{\partial W_j}{\partial \epsilon_i} = \underbrace{t_j\frac{dk_j}{d\epsilon_i} - \epsilon_j S'\frac{d\rho}{d\epsilon_i}}_{\text{IE}} + \underbrace{(F_e + V_e)\frac{de_j}{d\epsilon_i}}_{\text{EE}} \ . \tag{3.34}$$

As before, there are private income and environmental externalities where the second term in both equations is associated with the change in tax revenues from the consumption of good x_j^1. In contrast to the case of perfect complementarity, all externalities are ambiguous in sign. Recall that for $-\Gamma = 1 - \Phi$, ρ, k_j and e_j are insensitive to marginal tax changes. In other words, if this condition holds, all externalities equal zero and decentralized policy-making is also efficient. Otherwise, inserting the equilibrium tax rates and the comparative statics into (3.33) and (3.34) yields:

$$\frac{\partial W_j}{\partial \epsilon_i} = -\frac{\partial W_j}{\partial t_i} = -\frac{\alpha\beta(F_e + V_e)S'}{1 - \Phi + \Gamma - \beta\Gamma_i} \ , \tag{3.35}$$

implying that a marginal increase in ϵ_i or a marginal decrease in t_i have the same effect on welfare in country j. Since pollution and capital depend only on the difference $\epsilon_i - t_i$, the tax difference in the Nash equilibrium is set inefficiently high if equation (3.35) is negative. This is the case when pollution impacts on production are sufficiently large, i.e. $-\Gamma_i > (1 - \Phi)/[1 + \beta(n-2)]$. Otherwise, the tax difference is set inefficiently low. Therefore, we can state the following proposition.

Proposition 3.4 (Efficiency/Inefficiency under perfect substitutability)
When capital and emissions are perfect substitutes, the symmetric Nash equilibrium is efficient if the knife-edge condition $-\Gamma = 1 - \Phi$ holds or if $S' = 0$. Otherwise, an inefficiently high (low) tax difference $\epsilon_i - t_i$ prevails in the Nash equilibrium if pollution impacts on the MPC are sufficiently strong (weak).

In the Nash equilibrium, governments need to strike a balance between increasing private income and lowering pollution impacts in the home country. In addition, they may need to trade off capital outflows and domestic emissions reductions due to perfect substitutability. This trade-off becomes more complex, the higher are pollution impacts on the MPC. But for higher pollution impacts, countries are more likely to benefit from inefficiently high environmental regulation in terms of domestic investment and pollution.

Proposition 3.4 is consistent with the results obtained by Rauscher (1997b) in a similar setting but with exogenous capital supply. He also finds the possibility of inefficiently high or low pollution levels, depending on the size of the production externality and the elasticity of substitution between capital and emissions when both are inputs to production and can, therefore, be separately addressed by policy-makers. Inefficiently high environmental regulation prevails if capital is attracted rather than repelled by a marginal increase in environmental regulation. This occurs whenever the marginal benefit from this increase in terms of a higher MPC outweighs the cost associated with stricter environmental regulation.

3.4 Discussion

Having characterized the symmetric Nash equilibria in the cases where emissions and capital are perfect complements and substitutes, we discuss the results for two important special cases.

3.4.1 No environmental spillovers

If pollution stems purely from local emissions, i.e. $\beta = 0$, no environmental externality is imposed on other countries. In this case the symmetric Nash equilibrium in both cases (perfect complementarity/substitutability) is efficient. In case of perfect complementarity the capital tax and, in case of perfect substitutability, the difference between the consumption and the capital tax equal the SMD from emissions which is equal to $-\alpha(F_e + V_e)$. For the case of perfect substitutability the two taxes in the symmetric Nash equilibrium read:

$$t_i = 0 \ , \qquad \epsilon_i = -\alpha(F_e + V_e) \ . \tag{3.36}$$

The optimal environmental tax rate in each country thus exactly internalizes the externality imposed on its own household and its own firm. Together with the zero tax rate on capital, this implies efficiency of decentralized policy-making and resembles the result by Oates and Schwab (1988), amended by production externalities. The intuition is that a positive or negative capital tax rate would cause an additional distortion of the capital market by changing the price of capital and, thus, the capital-consumption decision of all households. This, in turn, would lead to a change in the pollution level in country i, as well as in all other countries, even though pollution itself does not spill over to other countries. If the consumption tax rate fully internalizes the externality from emissions, the use of an additional instrument is not in the best interest of all countries (at least if internal efficiency is guaranteed, as we assumed throughout the paper).

3.4.2 No production externalities

If there are no production externalities, i.e. $F_e = 0$, $F_{ke} = 0$ and, thus, $\Gamma = \Gamma_i = 0$, the case of perfect complementarity is essentially identical to the model discussed in E&R. In case of perfect substitutability, we obtain:

$$\hat{t}^S = -\alpha V_e \frac{\beta \Phi}{1-\Phi} < 0 \ , \tag{3.37a}$$

$$\hat{\epsilon}^S = -\alpha V_e \frac{1-(1-\beta)\Phi}{1-\Phi} > 0 \ , \tag{3.37b}$$

$$\widehat{(\epsilon - t)}^S = -\alpha V_e \quad < \quad -\alpha V_e[1+(n-1)\beta] = (\epsilon - t)^\star \ . \tag{3.37c}$$

The consumption tax in the symmetric Nash equilibrium is now unambiguously positive while capital is subsidized. If we interpret the production technology as renewable energy generation, we may refer to this capital subsidy as a 'green subsidy'.[4] Together, the two instruments only internalize the externality imposed on own utility, while the efficient tax-subsidy combination is $1+(n-1)\beta$-times higher. As a consequence, pollution levels are inefficiently high in the Nash equilibrium. This case illustrates that inefficiently low pollution levels may only prevail in equilibrium if pollution exerts a negative externality on production, providing governments with the incentive to attract capital by lowering emissions below their efficient level. Notably, although the consumption tax rate falls and the capital subsidy rises with a marginal increase in the degree of environmental spillover ($\partial \hat{\epsilon}^S / \partial \beta < 0$, $\partial \hat{t}^S / \partial \beta < 0$), the overall degree of internalization does not change with β ($\partial \widehat{(\epsilon - t)}^S / \partial \beta = 0$). This is in contrast to the

[4] Eichner and Runkel (2014) find in a different model set-up that governments have indeed an incentive to subsidize investment in green energy production under capital mobility.

case of perfect complementarity, where the tax rate is given by:

$$\hat{t}^C = -\alpha V_e \frac{(n-1)(1-\beta) - n\Phi}{(n-1) - n\Phi} \ . \tag{3.38}$$

Furthermore, the tax rate under perfect complementarity internalizes less of the environmental externality than the tax-subsidy combination in the case of perfect substitutability:

$$\hat{t}^C < (\widehat{\epsilon - t})^S \ . \tag{3.39}$$

Thus, the model assuming perfect substitutability is more optimistic with respect to efficiency for the whole range of environmental spillovers $\beta > 0$, even without considering a production externality.

3.5 Conclusion

We analyzed the interaction between mobile capital and non-cooperative environmental policy in two simple model frameworks, where capital and emissions were either perfect complements or perfect substitutes. We found that tax rates in the symmetric Nash equilibrium are always inefficiently low in the case of perfect complementarity but may be inefficiently high in case of perfect substitutability if pollution externalities on production are sufficiently high. Accounting for pollution externalities on production may crucially alter results: inefficiently high tax rates in equilibrium are only possible if these externalities are sufficiently strong.

Furthermore, we found that governments always tax capital use by firms at a strictly positive rate in case of perfect complementarity. By contrast, they may have an incentive to subsidize emissions and/or capital use by firms in case of perfect substitutability. If countries could agree to tax emissions in the latter case at the social marginal damage from emissions, this would remove all further capital tax competition by governments, assuming that internal efficiency is guaranteed.

Multiple avenues for further research are conceivable. Our extensions of the model by E&R with respect to the substitutability between emissions and capital, and pollution externalities on production are of the simplest perceivable form. We only analyze the situation of perfect complementarity and perfect substitutability neglecting all degrees of substitution in between. In addition, we only consider perfectly mobile capital. It would also be interesting to see how our results change for various degrees of capital mobility.

3.6 Appendix

Derivation of comparative statics with production externalities

Totally differentiating equations (3.1) and (3.3) for all $i = 1, \ldots, n$, and totally differentiating (3.9) in a symmetric equilibrium yields:

$$de_i = \alpha\Big(dk_i + \beta \sum_{j \neq i} dk_j\Big) \ , \tag{3.A.1}$$

$$dk_i = \frac{1}{F_{kk}}\Big(dt_i + d\rho - F_{ke} de_i\Big) \ , \tag{3.A.2}$$

$$\sum_{l=1}^{n} dk_l = nS' d\rho \ . \tag{3.A.3}$$

After inserting (3.A.1) into (3.A.2), using $\sum_{j \neq i} dk_j = nS'd\rho - dk_i$ from (3.A.3), we obtain:

$$dk_i = \frac{1}{F_{kk} + \alpha(1-\beta)F_{ke}}\Big(dt_i + [1 - \alpha\beta F_{ke} nS']\, d\rho\Big) \ . \tag{3.A.4}$$

For unilateral increases in t_i, plugging (3.A.4) for all $l = 1, \ldots, n$ into (3.A.3) and setting $dt_j = 0$ for all $j \neq i$ yields equation (3.10). Inserting the latter equation back into (3.A.2) implies equations (3.11a)–(3.11c) which can again be used to obtain (3.12a)–(3.12c). □

Derivation of comparative statics for perfect substitutability

Totally differentiating equations (3.3) and (3.18) for all $i = 1, \ldots, n$, using $dx_i^1 = -s_i'(d\rho + d\epsilon_i)$, and totally differentiating (3.24) in a symmetric equilibrium yields:

$$dk_i = \frac{1}{F_{kk}}\Big(dt_i + d\rho - F_{ke} de_i\Big) \ , \tag{3.A.5}$$

$$de_i = -\alpha \left[\Big(s_i' + \beta \sum_{j \neq i} s_j'\Big) d\rho + s_i' d\epsilon_i + \beta \sum_{j \neq i} s_j' d\epsilon_j\right] \ , \tag{3.A.6}$$

$$\sum_{l=1}^{n} dk_l = nS' d\rho + \sum_{l=1}^{n} S' d\epsilon_l \ . \tag{3.A.7}$$

After inserting (3.A.6) into (3.A.5), we obtain:

$$dk_i = \frac{1}{F_{kk}}\left[dt_i + \{1 + \alpha F_{ke}\Big(s_i' + \beta\sum_{j\neq i} s_j'\Big)\}d\rho + \alpha F_{ke}\{s_i' d\epsilon_i + \beta\sum_{j\neq i} s_j' d\epsilon_j\}\right] \ . \quad (3.A.8)$$

Plugging this equation into (3.A.7) for all $l = 1,\ldots,n$ and setting $dt_j = 0$ for all $j \neq i$ and $d\epsilon_l = 0$ for all l yields the equation to the left of (3.25). Similarly, setting $dt_l = 0$ for all l and $d\epsilon_j = 0$ for all $j \neq i$ yields the equation to the right of (3.25). Inserting these equations back into (3.A.6) and (3.A.5) implies equations (3.26a)–(3.26c) and (3.27a)–(3.27c). □

Proof of Proposition 3.2

We know that the global capital stock is – for given taxes/subsidies in all other countries – a function of ϵ_i and t_i. Totally differentiating $k = F(\epsilon_i, t_i)$ yields:

$$dk = \frac{\partial F}{\partial \epsilon_i} d\epsilon_i + \frac{\partial F}{\partial t_i} dt_i \ . \quad (3.A.9)$$

We also know from equation (3.26c) that

$$\frac{\partial k}{\partial \epsilon_i}\Big|_{dt_i=0} = -\frac{\partial k}{\partial t_i}\Big|_{d\epsilon_i=0} \ . \quad (3.A.10)$$

From these two equations follows immediately:

$$\frac{\partial F}{\partial \epsilon_i} = -\frac{\partial F}{\partial t_i} \quad \Leftrightarrow \quad \frac{\partial F}{\partial \epsilon_i} + \frac{\partial F}{\partial t_i} = 0 \ , \quad (3.A.11)$$

which is a partial differential equation.

Let $F(\epsilon_i, 0) = G(\epsilon_i)$ for $t_i = 0$. If $G(\epsilon_i)$ exists and is differentiable, then it follows from the calculus of partial differential equations:

$$F(\epsilon_i, t_i) = G(\epsilon_i - t_i). \quad (3.A.12)$$

That is, capital and emissions only depend on the difference $\epsilon_i - t_i$. The same reasoning applies to the level of global pollution e. □

Chapter 4

Non-renewable Resource Extraction and Interjurisdictional Competition across Space and Time

4.1 Introduction

Globalization has brought about considerable increases in international trade flows of man-made and natural capital. While the overall integration of financial markets and capital mobility are likely not much higher than one hundred years ago (Sachs and Warner, 1995), the trade of natural, non-renewable resources has not only increased significantly in magnitude but also relative to their production in the last few decades. For instance, the share of oil production traded internationally increased from 58% in 2000 to 65% in 2010 (BP, 2011).

Both capital and non-renewable resources such as fossil fuels are, in general, not consumed directly but serve as inputs to production. As such, they chase the highest returns internationally, and governments have an incentive to influence the allocation of capital and resources in their favor. Such strategic considerations between governments are reflected in the design of national tax systems. Evidence of this ongoing competition are declining statutory corporate income tax (CIT) rates in most regions of the world. For example, the average CIT rate in EU countries fell from 35.5% to 24.2% between 1997 and 2007 (KPMG, 2007). Similar but less pronounced trends have been 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). Competition for fossil resources cannot be measured as directly and is masked by an increasing public awareness of the adverse environmental effects associated with their use. However, some indication for such competition is that energy use by energy-intensive industries is subject to tax exemptions and various kinds of subsidization in many countries (GSI, 2010).

This paper analyzes the interaction between globalized capital and resource markets and the *strategic interaction* between jurisdictions in attracting mobile factors of production when an environmental externality caused by resource use needs to be internalized. Particular emphasis 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. Specifically, I consider jurisdictions, say countries, which non-cooperatively maximize their residents' lifetime utility by choosing from a set of environmental taxes on resource (energy) use and a source-based tax on capital investment. Competitive markets allocate capital and resources across countries and across periods. All taxes are levied on the demand-side, and resources which are assumed to be in finite supply can be extracted in the first or second period. First-period resource use causes transboundary pollution.

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 as in this paper). Furthermore, there exist huge differences in the endowment with fossil oil and gas across countries. These differences, however, are less pronounced when it comes to coal. Therefore, symmetry may be a good starting point for analyzing strategic behaviour by welfare-maximizing governments.

I find that unilateral increases in resource or capital taxes cause intratemporal leakage of resource use and thus pollution but also intertemporal leakage. For a positive capital supply elasticity, rising future resource taxes induce higher resource extraction in the present whereas rising future capital taxes may either speed up or slow down extraction, depending on the degree of complementarity between capital and resources. 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. A negative capital supply elasticity may reverse these market reactions.

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. If resource taxes are unavailable, future capital taxes tend to be more positive (negative) the lower (higher) is the degree of complementarity between the two production factors. If only resource taxes are at the governments' disposal, decentralized policy-making leads to falling resource taxes over time. with a strictly positive tax in the present and a strictly negative tax in the future.

Whenever capital *and* resource taxes are available, it is beneficial for governments to use a strictly positive capital tax rate in the future even though no revenue requirements are assumed in the model. The reason is that in general equilibrium an increase of the capital tax from zero to a strictly positive value unambiguously lowers the world market interest rate. This fall in the interest rate stimulates second-period resource demand in all other countries by inducing a fall in the second-period 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, first-period resource use and thus pollution go down.

I will refer to this channel as the *capital-tax-interest-rate channel.*

In a numerical example, it is shown that this general equilibrium channel is the stronger, the easier it is to substitute capital for resources. The intuition is that a capital tax then leads to a sharper decrease in the interest rate because of the induced substitution and thus causes a stronger increase in second-period resource use. If, by contrast, resources and capital are strong complements, an additional capital tax is not able to significantly lower aggregate first-period resource use. In this case, however, the private income externalities are small compared to the environmental externality.

4.2 Related literature

This paper bridges the gap between two strands of the literature: 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 literature on environmental policy and interjurisdictional competition 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 is Oates and Schwab (1988) who find efficiency of decentralized policy-making when there are no environmental 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. 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, the present paper is concerned with the role of the elasticity of substitution between capital and resources in production. Withagen and Halsema (2013) also set up a tax competition framework but reverse the timing of decisions such that households decide upon savings, anticipating government policies. 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 symmetric countries and externalities on utility only, capital mobility is found to aggravate transfrontier pollution problems (Rauscher, 2000, 2005) which may also be true in a setting with asymmetric countries (Rauscher, 1991). By contrast, environmental regulation may be inefficiently strict if emission externalities affect capital productivity (Rauscher, 1997a, 1997b).

The present paper also contributes to the resource economics literature which has mostly focused on single-country models or comparative static exercises in multi-country models, largely neglecting strategic interaction. 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), Golosov et al. (2014) and van der Meijden 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, it states that a greening of future tax policies will induce resource owners to speed up extraction in the present.

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 from unilaterally imposed policies.

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

4.3 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 1 as ‘the present’ or ‘today’ and period 2 as 'the future' or 'tomorrow'.

Governments are the strategic agents in this model and play a Nash game, taking the actions of all non-strategic followers, i.e. households and firms, into account. Households and resource extraction firms maximize intertemporally whereas production firms face a static profit maximization problem.

4.3.1 Production firms

In each country i, a representative firm produces an output good in each period $t = 1, 2$ 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 the non-renewable resource 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, $F_{kr} > 0$. 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 in capital and resources, implying strictly positive profits.[1]

Installed production capacity results from previous capital investment and is thus fixed in the short run. In other words, the first-period stock of capital $\bar{k}$ employed in each country is 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.[2]

Given that country i levies a unit source-based tax κ^i on capital[3] and a period-specific (environmental) tax t_t^i on resource use, after-tax profits of the representative firm in country i are:

$$\pi_1^i = f(r_1^i) - (p_1 + t_1^i)r_1^i \ , \qquad (4.1)$$

$$\pi_2^i = F(k^i, r_2^i) - (\rho + \kappa^i)k^i - (p_2 + t_2^i)r_2^i \ . \qquad (4.2)$$

---

[1] An alternative interpretation is that the production function is linearly homogenous in capital, resources and *labor* as, for example, in Hassler and Krusell (2012). If labor is fixed because of constant population size, deducting capital and resource costs from profits yields labor income.

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

[3] 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.

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

$$f_r(r_1^i) - t_1^i = p_1 , \tag{4.3}$$
$$F_r(k^i, r_2^i) - t_2^i = p_2 , \tag{4.4}$$
$$F_k(k^i, r_2^i) - \kappa_i = \rho . \tag{4.5}$$

4.3.2 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 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. Profits in period t are given by:

$$\Pi_t^i = p_t q_t^i . \tag{4.6}$$

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:

$$p_2 = p_1(1+\rho) . \tag{4.7}$$

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 a competitive resource market, resource demand alone determines the equilibrium quantities supplied as long as equation (4.7) holds.[4] 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, undetermined. Only *in aggregate* supply must meet demand, $\sum_{l=1}^n q_1^l = \sum_{l=1}^n r_1^l$ but there is a continuum of supplied quantities that satisfy this equality. Such asymmetric extraction across countries implies differing resource incomes and thus savings s^i from first-period income. In a symmetric equilibrium, as analyzed later on, players use the same strategy, i.e., the same tax rates. Identical tax

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

rates, however, can only be a best response if extraction occurs symmetrically such that $q_t^i = r_t^i$ and $s^i = k^i$.[5]

4.3.3 Households

Each country is populated by a representative household who owns both the production and the resource extraction firm in her country of origin and thus receives the corresponding profits π_t^i and Π_t^i. Any positive revenues from taxing production inputs are returned lump-sum to consumers in each period:

$$\tau_1^i = t_1^i r_1^i \ , \tag{4.8}$$

$$\tau_2^i = t_2^i r_2^i + \kappa^i k^i \ , \tag{4.9}$$

where τ_t^i is the sign-unconstrained lump-sum transfer in period t. The assumption on lump-sum transfers implies that no further distortions such as from the provision of physical public goods arise in the model.

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

$$c_1^i = \pi_1^i + \Pi_1^i + \tau_1^i - s^i \ , \tag{4.10}$$

$$c_2^i = \pi_2^i + \Pi_2^i + \tau_2^i + (1+\rho)s^i \ . \tag{4.11}$$

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.[6] Welfare of the representative household in country i reads:

$$W^i = U(c_1^i) - D(r_1) + \epsilon c_2^i \ , \tag{4.12}$$

where $\epsilon \leq 1$ is the discount factor. U is assumed to be concave and twice differentiable

[5] Extraction paths that are symmetric across countries even in asymmetric equilibria could be obtained by introducing convex (flow- or stock-dependent) extraction costs. Then, the wells with the least cost would be exploited first. If extraction costs are identical for all countries, all wells would be depleted equally fast.

[6] 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. If resources are fully extracted like in this model, the damage in the second period is a function of Q and thus a constant.

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 (4.12) subject to budget constraints (4.10) and (4.11), taking firm profits, lump-sum transfers and damages as given. From the necessary and sufficient condition for a household maximum (Euler equation),

$$U'(c_1^i) - \epsilon(1+\rho) = 0 \ , \tag{4.13}$$

we obtain for marginal increases in the interest rate ρ and in first-period income π_1^i, Π_1^i or τ_1^i:

$$\frac{\partial s^i}{\partial \rho} = -\frac{\epsilon}{U''(c_1^i)} > 0 \ , \tag{4.14}$$

$$\frac{\partial s^i}{\partial \pi_1^i} = \frac{\partial s^i}{\partial \Pi_1^i} = \frac{\partial s^i}{\partial \tau_1^i} = 1 \ . \tag{4.15}$$

Equation (4.14) implies a positive capital supply elasticity $(\partial s^i/\partial\rho)\rho/s^i > 0$, and (4.15) states that any increase in profits or the lump-sum transfer in the first period, starting from an equilibrium, increases only second-period consumption via the associated increase in savings and leaves first-period consumption unaffected.

4.4 Global capital and resource market equilibria

4.4.1 Capital market

Capital is assumed to be perfectly mobile between countries and traded on a global capital market. As first-period capital is assumed to be immobile, a capital market comes into existence in the second period. The equilibrium interest rate ρ is found by equating capital demand by production firms as described by equation (4.5) and capital supply by households:

$$\sum_{l=1}^{n} k^l = \sum_{l=1}^{n} s^l \ . \tag{4.16}$$

This equation determines ρ as a function of the resource prices p_1 and p_2 and all tax rates in all countries.

4.4.2 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 (4.7). The second necessary condition is:

$$\sum_{l=1}^{n} r_1^l + \sum_{l=1}^{n} r_2^l = Q \ . \tag{4.17}$$

The resource endowment in each country is fixed such that the right-hand side of equation (4.17) is a constant. The resource demand functions on the left-hand side are implicitly given by equations (4.3) and (4.4). Hotelling's rule and equation (4.17) jointly determine the equilibrium world market prices p_1 and p_2 as functions of the interest rate ρ and the tax rates in all countries.

The equilibrium levels of capital and resources used in production are determined by the first-order conditions of profit maximization, (4.3)–(4.5), Hotelling's rule (4.7), equation (4.13) and the market-clearing conditions (4.16) and (4.17), and can be expressed as functions of the tax rates in all countries.

4.4.3 Comparative statics

To obtain the comparative statics of unilateral marginal tax increases, we totally differentiate equations (4.3)–(4.5) for all $i = 1, \ldots, n$ and (4.7) and insert them into the differentiated conditions (4.16) and (4.17), using (4.14) and (4.15). The comparative statics with respect to second-period tax rates can be regarded as announcement effects. Starting from a symmetric equilibrium where $k^i = s^i = s$ holds, we arrive at the following results (derived in the Appendix).

4.4.3.1 Resource taxes

For unilateral marginal increases in the resource taxes t_1^i (left-hand side) and t_2^i (right-hand side of the following equations), it holds:

$$\frac{\partial \rho}{\partial t_1^i} = -\frac{(1+\rho)(F_{kr} - f_r F_{kk})}{n\Delta} > 0 \ , \qquad \frac{\partial \rho}{\partial t_2^i} = \frac{F_{kr} - f_r F_{kk}}{n\Delta} < 0 \ , \tag{4.18a}$$

$$\frac{\partial p_1}{\partial t_1^i} = \frac{p_1 F_{kr} - \Phi - \Theta}{n\Delta} < 0 \ , \qquad \frac{\partial p_1}{\partial t_2^i} = \frac{f_{rr}\Omega}{n\Delta} < 0 \ , \tag{4.18b}$$

$$\frac{\partial p_2}{\partial t_1^i} = -\frac{(1+\rho)(\Phi - f_r F_{kr})}{n\Delta} < 0 \ , \qquad \frac{\partial p_2}{\partial t_2^i} = \frac{\Phi - f_r F_{kr} - \Delta}{n\Delta} < 0 \ , \tag{4.18c}$$

where $\Gamma = F_{kk}F_{rr} - (F_{kr})^2 > 0$, $\Phi = F_{rr} - \partial s/\partial\rho\Gamma < 0$, $\Omega = \partial s/\partial\rho F_{kk} - 1 < 0$, $\Theta = f_r(p_1F_{kk} - F_{kr}) < 0$ and $\Delta = \Phi - p_1F_{kr} - (1+\rho)f_{rr}\Omega + \Theta < 0$.[7]

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 with a purely substitutive production technology, $F_{kr} = 0$, the interest rate is affected since a change in resource use in the first period and the associated change in production goes along with a change in savings and thus alters 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 resource use induced by the tax increase changes capital demand through its impact on the marginal product of capital.

For resource use and pollution, we obtain:

$$\frac{\partial r_1^i}{\partial t_1^i} = \frac{(n-1)\Delta - (1+\rho)f_{rr}\Omega}{nf_{rr}\Delta} < 0 \;, \qquad \frac{\partial r_1^i}{\partial t_2^i} = \frac{\Omega}{n\Delta} > 0 \;, \tag{4.19a}$$

$$\frac{\partial r_1^j}{\partial t_1^i} = \frac{p_1F_{kr} - \Phi - \Theta}{nf_{rr}\Delta} > 0 \;, \qquad \frac{\partial r_1^j}{\partial t_2^i} = \frac{\Omega}{n\Delta} > 0 \;, \tag{4.19b}$$

$$\frac{\partial r_1}{\partial t_1^i} = -\frac{(1+\rho)\Omega}{\Delta} < 0 \;, \qquad \frac{\partial r_1}{\partial t_2^i} = \frac{\Omega}{\Delta} > 0 \;, \tag{4.19c}$$

$$\frac{\partial r_2^i}{\partial t_1^i} = \frac{(1+\rho)\Omega}{n\Delta} > 0 \;, \qquad \frac{\partial r_2^i}{\partial t_2^i} = \frac{(n-1)F_{kk}\Delta - \Gamma\Omega}{n\Gamma\Delta} < 0 \;, \tag{4.19d}$$

$$\frac{\partial r_2^j}{\partial t_1^i} = \frac{(1+\rho)\Omega}{n\Delta} > 0 \;, \qquad \frac{\partial r_2^j}{\partial t_2^i} = -\frac{F_{kk}\Delta + \Gamma\Omega}{n\Gamma\Delta} > 0 \;, \tag{4.19e}$$

$$\frac{\partial r_2}{\partial t_1^i} = \frac{(1+\rho)\Omega}{\Delta} > 0 \;, \qquad \frac{\partial r_2}{\partial t_2^i} = -\frac{\Omega}{\Delta} < 0 \;, \tag{4.19f}$$

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 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

[7] For production functions with constant returns to scale, Γ equals zero; with decreasing returns to scale, $\Gamma > 0$. Note that later on pure profits, i.e., decreasing returns to scale in capital and resources are needed. Otherwise, zero second-period tax rates may result, see equations (4.33) and (4.37).

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).

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:

$$\frac{\partial k^i}{\partial t_1^i} = \frac{(1+\rho)\left[f_r - \frac{\partial s}{\partial \rho}F_{kr}\right]}{n\Delta} \gtreqless 0 \; , \quad \frac{\partial k^i}{\partial t_2^i} = \frac{F_{kr}[\frac{\partial s}{\partial \rho}\Gamma - (n-1)\Delta] - f_r\Gamma}{n\Gamma\Delta} \gtreqless 0 \; , \tag{4.20a}$$

$$\frac{\partial k^j}{\partial t_1^i} = \frac{(1+\rho)\left[f_r - \frac{\partial s}{\partial \rho}F_{kr}\right]}{n\Delta} \gtreqless 0 \; , \quad \frac{\partial k^j}{\partial t_2^i} = \frac{F_{kr}[\frac{\partial s}{\partial \rho}\Gamma + \Delta] - f_r\Gamma}{n\Gamma\Delta} > 0 \; , \tag{4.20b}$$

$$\frac{\partial k}{\partial t_1^i} = \frac{(1+\rho)\left[f_r - \frac{\partial s}{\partial \rho}F_{kr}\right]}{\Delta} \gtreqless 0 \; , \quad \frac{\partial k}{\partial t_2^i} = \frac{\frac{\partial s}{\partial \rho}F_{kr} - f_r}{\Delta} \gtreqless 0 \; . \tag{4.20c}$$

For a purely substitutive relationship, $F_{kr} = 0$, the change in capital use is driven by the change in savings due to the intertemporal reallocation of resource use. A marginal change in t_t^i lowers domestic and aggregate resource use in period t but increases resource use in the other period. If it increases, e.g., first-period resource use, more output is produced and the associated increase in profits translates one-to-one into higher savings and thus higher capital use in the second period. With complementarity, capital use is also affected by the change in resource use following marginal tax changes. For our example from above, declining second-period resource use goes along with decreasing capital demand and (as we will also see in Section 4.5.3) an interest rate that is decreasing by more than under perfect substitutability. This effect counteracts the first effect of increased savings, and it is unclear which effect prevails in equilibrium. Only for an increase in t_2^i does investment in all countries $j \neq i$ unambiguously rise.

4.4.3.2 Capital tax

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

$$\frac{\partial \rho}{\partial \kappa^i} = -\frac{(1+\rho)f_{rr} + F_{rr} - f_r F_{kr}}{n\Delta} < 0 \; , \tag{4.21a}$$

$$\frac{\partial p_1}{\partial \kappa^i} = \frac{f_{rr}[p_1 - \frac{\partial s}{\partial \rho} F_{kr}]}{n\Delta} \gtreqless 0 \ , \tag{4.21b}$$

$$\frac{\partial p_2}{\partial \kappa^i} = -\frac{p_1(F_{rr} - f_r F_{kr}) + (1+\rho) f_{rr} \frac{\partial s}{\partial \rho} F_{kr}}{n\Delta} < 0 \ . \tag{4.21c}$$

As expected, 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, we find:

$$\frac{\partial k^i}{\partial \kappa^i} = \frac{(n-1)F_{rr}\Delta - \frac{\partial s}{\partial \rho}\Gamma[(1+\rho) f_{rr} + F_{rr}] + p_1 f_r \Gamma}{n\Gamma\Delta} < 0 \ , \tag{4.22a}$$

$$\frac{\partial k^j}{\partial \kappa^i} = \frac{F_{kr}[p_1 F_{rr} + (1+\rho) f_{rr} \frac{\partial s}{\partial \rho} F_{kr}] - F_{rr}[(1+\rho) f_{rr} + F_{rr}] + p_1 f_r \Gamma}{n\Gamma\Delta} > 0 \ , \tag{4.22b}$$

$$\frac{\partial k}{\partial \kappa^i} = \frac{p_1 f_r - \frac{\partial s}{\partial \rho}[(1+\rho) f_{rr} + F_{rr}]}{\Delta} < 0 \ . \tag{4.22c}$$

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:

$$\frac{\partial r_1^i}{\partial \kappa^i} = \frac{p_1 - \frac{\partial s}{\partial \rho} F_{kr}}{n\Delta} \gtreqless 0 \ , \tag{4.23a}$$

$$\frac{\partial r_1^j}{\partial \kappa^i} = \frac{p_1 - \frac{\partial s}{\partial \rho} F_{kr}}{n\Delta} \gtreqless 0 \ , \tag{4.23b}$$

$$\frac{\partial r_1}{\partial \kappa^i} = \frac{p_1 - \frac{\partial s}{\partial \rho} F_{kr}}{\Delta} \gtreqless 0 \ , \tag{4.23c}$$

$$\frac{\partial r_2^i}{\partial \kappa^i} = -\frac{(n-1)F_{kr}\Delta + \Gamma[p_1 - \frac{\partial s}{\partial \rho} F_{kr}]}{n\Gamma\Delta} \gtreqless 0 \ , \tag{4.23d}$$

$$\frac{\partial r_2^j}{\partial \kappa^i} = \frac{F_{kr}\Delta - \Gamma[p_1 - \frac{\partial s}{\partial \rho} F_{kr}]}{n\Gamma\Delta} > 0 \ , \tag{4.23e}$$

$$\frac{\partial r_2}{\partial \kappa^i} = -\frac{p_1 - \frac{\partial s}{\partial \rho} F_{kr}}{\Delta} \gtreqless 0 \ . \tag{4.23f}$$

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 firms in country i due to the marginal tax increase, they 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 resource use and pollution in the first period results, going along with an increase in p_1. A unilaterally imposed increase in future 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. As will be shown in the simulations in Section 4.5.3, a sufficiently high degree of complementarity, i.e., a sufficiently high value of F_{kr}, causes this term to be negative and leads 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 marginal increase in one country's future 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 as a consequence of the decrease in ρ associated with the increase in κ^i. With less capital supply and investment in the second period, also resource use in the second period decreases and first-period resource use and pollution go up.

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

Proposition 4.1 (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.*

4.5 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.

4.5.1 Pareto-optimal policies

Pareto-optimal policies are found by maximizing lifetime utility W^i, equation (4.12), s.t. $W^j = \bar{W}^j$, $\forall j \neq i$, by choosing κ^i, t_1^i and t_2^i. Further constraints are the budget constraints of each household, (4.10) and (4.11), where firm profits and lump-sum transfers (both of which are exogenous from the perspective of households) are replaced by (4.1) and (4.2) respectively (4.8) and (4.9). Furthermore, the conditions of utility maximization, (4.13)–(4.15), profit maximization, (4.3)–(4.7), and the market reactions as described by (4.18a)–(4.23f) are considered. Focusing on the symmetric solution with $s^i = k^i = s$ and $q_t^i = r_t^i$, the first-order conditions for country i read:[8]

$$(1+\rho)t_1^i \frac{\partial r_1}{\partial t_1^i} + t_2^i \frac{\partial r_2}{\partial t_1^i} + \kappa^i \frac{\partial k}{\partial t_1^i} - \frac{nD'(r_1)}{\epsilon} \frac{\partial r_1}{\partial t_1^i} = 0 \ , \tag{4.24}$$

$$(1+\rho)t_1^i \frac{\partial r_1}{\partial t_2^i} + t_2^i \frac{\partial r_2}{\partial t_2^i} + \kappa^i \frac{\partial k}{\partial t_2^i} - \frac{nD'(r_1)}{\epsilon} \frac{\partial r_1}{\partial t_2^i} = 0 \ , \tag{4.25}$$

$$(1+\rho)t_1^i \frac{\partial r_1}{\partial \kappa^i} + t_2^i \frac{\partial r_2}{\partial \kappa^i} + \kappa^i \frac{\partial k}{\partial \kappa^i} - \frac{nD'(r_1)}{\epsilon} \frac{\partial r_1}{\partial \kappa^i} = 0 \ . \tag{4.26}$$

Rearranging these conditions and denoting $\kappa^i = \kappa^*$, $t_1^i = t_1^*$ and $t_2^i = t_2^*$ yields the following Pareto-optimal tax rates:

$$\kappa^* = 0 \ , \tag{4.27}$$

$$t_1^* - \frac{t_2^*}{1+\rho} = \frac{nD'(r_1)}{U'(c_1^i)} = \frac{nD'(r_1)}{\epsilon(1+\rho)} \ . \tag{4.28}$$

The Pareto-optimal capital tax rate κ^* equals zero. The social marginal environmental

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[8] Note again that the resource quantities supplied by each country are, in principle, undetermined as argued in Section 4.3.2 (only in symmetric equilibrium, we have $q_t^i = r_t^i$). This also implies that the derivatives of the supplied quantities with respect to the tax rates $\Box = \kappa^i, t_1^i, t_2^i$ are zero for any time period t: $\partial q_t^i / \partial \Box = 0$. With symmetric extraction costs, we would have: $\partial q_t^i / \partial \Box = (1/n) \partial r_t / \partial \Box$, 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.

damage (SMD) $nD'(r_1)$ 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 t_1^* and t_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 (4.28) 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.[9] 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 is able to incentivize firms to postpone extraction relative to a laissez-faire scenario without taxes.

4.5.2 Dezentralized equilibrium

We can now proceed to characterize the equilibrium of the Nash game. I assume 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.

The benevolent government in each country non-cooperatively maximizes its resident's lifetime utility by choosing κ^i, t_1^i and t_2^i, taking the policies of all other countries as given. To this end, it takes the household's budget constraint into account, equations (4.10) and (4.11), replacing firm profits by (4.1) and (4.2) and lump-sum transfers by (4.8) and (4.9). It also considers the conditions of utility maximization, (4.13)–(4.15), profit maximization, (4.3)–(4.7), and the market reactions (4.18a)–(4.18c), (4.19a), (4.19d), (4.20a), (4.21a)–(4.21c), (4.22a), (4.23a) and (4.23d). Assuming that a symmetric equilibrium with an interior solution exists, it is described by the following first-order conditions:

$$(1+\rho)t_1^i\frac{\partial r_1^i}{\partial t_1^i}+t_2^i\frac{\partial r_2^i}{\partial t_1^i}+\kappa^i\frac{\partial k^i}{\partial t_1^i}-\frac{D'(r_1)}{\epsilon}\frac{\partial r_1}{\partial t_1^i}=0\ , \tag{4.29}$$

$$(1+\rho)t_1^i\frac{\partial r_1^i}{\partial t_2^i}+t_2^i\frac{\partial r_2^i}{\partial t_2^i}+\kappa^i\frac{\partial k^i}{\partial t_2^i}-\frac{D'(r_1)}{\epsilon}\frac{\partial r_1}{\partial t_2^i}=0\ , \tag{4.30}$$

$$(1+\rho)t_1^i\frac{\partial r_1^i}{\partial \kappa^i}+t_2^i\frac{\partial r_2^i}{\partial \kappa^i}+\kappa^i\frac{\partial k^i}{\partial \kappa^i}-\frac{D'(r_1)}{\epsilon}\frac{\partial r_1}{\partial \kappa^i}=0\ . \tag{4.31}$$

Each government trades off the marginal benefits with the marginal costs of tax changes. These changes affect environmental damage by altering aggregate resource

[9] Pareto-optimal resource tax rates that decline over time have also been found in one-country models, see, e.g., Golosov et al. (2014) and Sinclair (1992, 1994).

use in the first period, and tax revenues by altering the tax bases. Compared to equations (4.24)–(4.26), we observe that governments do not take into account the effects of their policies on aggregate variables and aggregate pollution damages. To gain some understanding of the governments' strategic behaviour, 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.

4.5.2.1 Nash equilibrium with resource taxes only

If the government has only resource taxes at its disposal, equation (4.31) drops out, and the optimal tax rates in the symmetric Nash equilibrium in country i can be obtained by rearranging conditions (4.29) and (4.30) for $\kappa^i = 0$:

$$t_1^i = -\frac{nD'(r_1)}{\epsilon}\frac{f_{rr}F_{kk}\Omega}{(n-1)F_{kk}\Delta - \Omega\left[\Gamma + (1+\rho)f_{rr}F_{kk}\right]} > 0 \ , \tag{4.32}$$

$$t_2^i = \frac{nD'(r_1)}{\epsilon}\frac{\Gamma\Omega}{(n-1)F_{kk}\Delta - \Omega\left[\Gamma + (1+\rho)f_{rr}F_{kk}\right]} < 0 \ . \tag{4.33}$$

A marginal increase in t_1^i and a decrease in t_2^i have the same qualitative effects on domestic welfare, see equations (4.29)–(4.30). They lower domestic and aggregate resource use in the first period, thereby reducing environmental damage and increasing resource tax revenue in the second period. The associated marginal cost is the loss of resource tax revenue in the first period. Although the resource tax 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. Furthermore, for given taxes in all other countries, aggregate resource use in the first period depends only on the difference $t_1^i - t_2^i/(1+\rho)$. This is established in the following lemma the proof of which can be found in the Appendix.

Lemma 4.1 (Aggregate resource use and pollution)
For given tax policies in all other countries, aggregate resource use and pollution are determined by the difference $t_1^i - t_2^i/(1+\rho)$.

Using Lemma 4.1 and equations (4.32) and (4.33), it is straightforward to prove the following proposition.

Proposition 4.2 (Inefficiency of (t_1^i, t_2^i)-Nash equilibrium)
The Nash equilibrium with resource taxes only is inefficient as

$$t_1^i - \frac{t_2^i}{1+\rho} = -\frac{nD'(r_1)}{\epsilon(1+\rho)} \frac{\Omega\left[\Gamma + (1+\rho) f_{rr} F_{kk}\right]}{(n-1)F_{kk}\Delta - \Omega\left[\Gamma + (1+\rho) f_{rr} F_{kk}\right]} \neq SMD\ . \tag{4.34}$$

It can easily be shown that the second fraction in this equation is smaller than one in absolute value. Therefore, we may suspect that the Nash equilibrium entails inefficiently high first-period resource use. However, the interest rate and marginal damages depend on the equilibrium levels of capital and resources used in production. As these differ for Pareto-optimal and Nash equilibrium policies, we cannot simply compare the Pareto-optimal tax-subsidy combination with the tax-subsidy combination in the Nash equilibrium. 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. A positive (negative) externality implies that the tax rate in the Nash equilibrium is set inefficiently low. For $\Box = t_1, t_2$, we obtain:

$$\frac{\partial W^j}{\partial \Box^i} = -D'(r_1)\frac{\partial r_1}{\partial \Box^i} + \epsilon(1+\rho)t_1^j \frac{\partial r_1^j}{\partial \Box^i} + \epsilon t_2^j \frac{\partial r_2^j}{\partial \Box^i}\ . \tag{4.35}$$

Inserting the Nash equilibrium tax rates and the comparative statics results into (4.35), it can be shown that a marginal increase in t_1^i exerts a positive environmental externality on country j which points to an inefficiently low equilibrium tax rate. Additionally, two private income externalities arise that change the tax bases in country j due to resource mobility.[10] They have different signs but are strictly positive in aggregate, indicating again inefficiently low first-period tax rates in the Nash equilibrium. A marginal increase in t_2^i (the subsidy becomes smaller), by contrast, induces a negative environmental externality and private income externalities that are in aggregate also negative. This implies that the tax rate has been set inefficiently high, i.e., the subsidy is inefficiently low. Furthermore, we can establish the following lemma.

Lemma 4.2 (Policy externalities of t_1^i and t_2^i)
A marginal increase in t_1^i has the opposite effect in present value terms of a marginal

[10] 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 but the 'private income' externalities could then be called 'fiscal'.

increase in t_2^i:

$$\frac{\partial W^j}{\partial t_2^i} = -\frac{1}{1+\rho}\frac{\partial W^j}{\partial t_1^i} = -\frac{nD'(r_1)F_{kk}\Omega}{(n-1)F_{kk}\Delta - \Omega[\Gamma + (1+\rho)f_{rr}F_{kk}]} < 0 \ . \tag{4.36}$$

All externalities are related to the environmental damage in country j. A marginal increase in the tax-subsidy combination $t_1^i - t_2^i/(1+\rho)$ which can be achieved by increasing t_1^i or decreasing t_2^i thus exerts a positive externality on the welfare in all other countries such that we can state the following proposition.

Proposition 4.3 (Inefficiently high pollution in (t_1^i, t_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 and pollution are inefficiently high.

Like in Eichner and Runkel (2012) for perfect spillovers, environmental and private income externalities go in the same direction (for perfect spillovers as in this model) and imply inefficiently low equilibrium tax rates and thus inefficiently high resource use in the first period. By contrast, factor mobility has been shown to increase environmental quality when pollution affects the marginal productivity of capital (Rauscher, 1997) or when households anticipate government policies (Withagen and Halsema, 2013).

4.5.2.2 Nash equilibrium with capital tax only

If the government is restricted to use a capital tax, conditions (4.29) and (4.30) drop out. A marginal capital tax increase reduces tax revenue due to the associated capital outflow but may increase or decrease aggregate resource use and thus pollution. For $t_1^i = t_2^i = 0$, the first-order condition (4.31) in the symmetric Nash equilibrium in country i can be written as:

$$\kappa^i = \frac{nD'(r_1)}{\epsilon}\frac{\left[p_1 - \frac{\partial s}{\partial \rho}F_{kr}\right]\Gamma}{(n-1)F_{rr}\Delta - \frac{\partial s}{\partial \rho}\Gamma\left[(1+\rho)f_{rr} + F_{rr}\right] + p_1 f_r \Gamma} \ . \tag{4.37}$$

The sign of the capital tax solely depends on the term $p_1 - \partial s/\partial\rho F_{kr}$ in the numerator:

$$\kappa^i \gtreqless 0 \Leftrightarrow p_1 - \frac{\partial s}{\partial \rho}F_{kr} \gtreqless 0 \ , \tag{4.38}$$

and is thus – like nearly all ambiguous comparative statics results in Section 4.4.3.2 – driven by the complex interplay of p_1, $\partial s/\partial\rho$ and F_{kr}. Specifically, 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. Again, we can suspect (and it will be shown in the numerical illustrations of Section 4.5.3) that inefficiently high first-period extraction prevails since the externality-generating good cannot be targeted by the government directly.[11]

4.5.2.3 Nash equilibrium with resource and capital taxes

If each government is armed with the full set of tax instruments, additional considerations enter the government's trade-off between marginal costs and marginal benefits. In particular, marginal changes in resource taxes now also 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 t_1^i or t_2^i. Similarly, a marginal capital tax increase may positively or negatively affect resource tax revenues. The first-order conditions (4.29)–(4.31) can be rearranged to yield:

$$\kappa^i = \frac{D'(r_1)}{\epsilon} \frac{(n-1)(F_{kr} - p_1 F_{kk})}{\frac{\partial s}{\partial \rho}\left[\Gamma + (1+\rho) f_{rr} F_{kk}\right] - (n-1)\Delta} > 0 \ , \tag{4.39}$$

$$t_1^i = -\frac{D'(r_1)}{\epsilon} \frac{f_{rr}\left[(n-1) - n\frac{\partial s}{\partial \rho} F_{kk}\right]}{\frac{\partial s}{\partial \rho}\left[\Gamma + (1+\rho) f_{rr} F_{kk}\right] - (n-1)\Delta} > 0 \ , \tag{4.40}$$

$$t_2^i = \frac{D'(r_1)}{\epsilon} \frac{(n-1)(F_{rr} - p_1 F_{kr}) - n\frac{\partial s}{\partial \rho}\Gamma}{\frac{\partial s}{\partial \rho}\left[\Gamma + (1+\rho) f_{rr} F_{kk}\right] - (n-1)\Delta} < 0 \ . \tag{4.41}$$

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. Note that moving from the Nash equilibrium with resource taxes only to the Nash equilibrium with all instruments does not only introduce the capital tax but also changes the size of the resource taxes. This is why the comparative statics of a marginal capital tax increase cannot shed light on the incentives that lead to the unambiguous sign of the capital tax in equilibrium. However, the terms in the numerator of equation (4.39) give an explanation of the effects at work. By increasing the capital tax from zero to a positive value, the government induces all other $n-1$ countries to use more

[11] Calculating the policy externalities does not yield much insight because the result would relate to a constrained Pareto-optimum with the capital tax as the only available instrument.

resources in the second and less resources in the first period, thereby lowering domestic environmental pollution. This occurs through a channel which I will refer to as the *capital-tax-interest-rate channel*. The latter unfolds its effects through the associated decrease in the interest rate (see equation (4.21a)). 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 (4.39)). Second, there is a Hotelling rule effect (second term in the numerator) which holds even for a purely substitutive technology. The fall in the interest rate is accompanied by a fall in p_2 which also induces production firms abroad to use more resources in the second period. The positive first-period and negative second-period resource taxes are brought about, among others, by an effect that works through the supply-side of capital. Increasing t_1^i or decreasing t_2^i increases the interest rate which leads, *ceteris paribus*, to higher savings in *all* countries due to the substitution effect and thus higher private income from capital taxation.

Assessing the efficiency properties of this Nash equilibrium is slightly more complicated than before since the different policy externalities contain only information as to whether *each* tax rate is set inefficiently high or low in equilibrium. To assess whether all tax rates taken together imply inefficiently high or low aggregate resource use in the first period, assume that the government in country i is able to control r_1^i directly. Then, the impact of a marginal change in r_1^i on welfare in country $j \neq i$, evaluated at the symmetric Nash equilibrium, is as follows:

$$\frac{\partial W^j}{\partial r_1^i} = -\,D'(r_1)\left[1 + (n-1)\frac{\partial r_1^j}{\partial p_1}\frac{\partial p_1}{\partial r_1^i}\right] + \epsilon(1+\rho)t_1^j\frac{\partial r_1^j}{\partial p_1}\frac{\partial p_1}{\partial r_1^i} + \\ + \epsilon\left[t_2^j\Big(\frac{\partial r_2^j}{\partial p_2}\frac{\partial p_2}{\partial r_1^i} + \frac{\partial r_2^j}{\partial \rho}\frac{\partial \rho}{\partial r_1^i}\Big) + \kappa^j\Big(\frac{\partial k^j}{\partial p_2}\frac{\partial p_2}{\partial r_1^i} + \frac{\partial k^j}{\partial \rho}\frac{\partial \rho}{\partial r_1^i}\Big)\right] \,. \tag{4.42}$$

Unsurprisingly, we have environmental and private income externalities as before. Using the comparative statics for $\partial p_1/\partial r_1^i$, $\partial p_2/\partial r_1^i$ and $\partial \rho/\partial r_1^i$ derived in the Appendix, it is easy to prove that all private income externalities together go again in the same direction as the environmental externality. Therefore, we can establish the following proposition.

Proposition 4.4 (Inefficiently high pollution in (t_1^i, t_2^i, κ^i)-Nash equilibrium) *In the Nash equilibrium with all instruments, first-period resource use and thus pollution* *is inefficiently high as:*

$$\frac{\partial W^j}{\partial r_1^i} = \frac{nD'(r_1)(1+\rho)f_{rr}\left[(n-1-n\frac{\partial s}{\partial \rho}F_{kk})\Delta + (1+\rho)f_{rr}\Omega\frac{\partial s}{\partial \rho}F_{kk}\right]}{\left[\frac{\partial s}{\partial \rho}\Big(\Gamma + (1+\rho)f_{rr}F_{kk}\Big) - (n-1)\Delta\right]\left[(n-1)\Delta - n(1+\rho)f_{rr}\Omega\right]} < 0 \ . \quad (4.43)$$

In this regard, the paper generalizes the results obtained by Eichner and Runkel (2012) and Rauscher (2000, 2005) who find that capital mobility aggravates transfrontier pollution problems (at least for perfect pollution spillovers).

4.5.3 Numerical illustration

So far, we can state that the Nash equilibria examined in Sections 4.5.2.1 and 4.5.2.3 and supposedly the capital-tax-only scenario in Section 4.5.2.2 entail inefficiently high resource use in the present. In order to quantify the effects at work, particularly the additional distortion due to factor mobility, some numerical illustrations are provided. I am particularly interested in how the size of the distortions depends on the elasticity of substitution between capital and resources.

To have another benchmark, I first sketch the Nash equilibrium under autarky, i.e., when factors 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. The modified comparative statics of unilateral marginal tax increases can easily be derived by setting $n = 1$ in equations (4.18a)–(4.23f). Note that there is no leakage anymore since capital and resources are not traded. Taking these modified comparative statics results into account, government maximization yields the following tax rates κ^{i0}, t_1^{i0} and t_2^{i0} in the autarky Nash equilibrium in each country:

$$\kappa^{i0} = 0 \ , \quad (4.44)$$

$$t_1^{i0} - \frac{t_2^{i0}}{1+\rho^i} = \frac{D'(r_1)}{\epsilon(1+\rho^i)} \ . \quad (4.45)$$

The government now has one degree of freedom in setting the resource tax-subsidy combination to internalize the environmental externality imposed on own utility. This is the standard textbook case where no additional distortions are present.[12] As the capital and resource allocation in other countries cannot be influenced via tax policies,

[12] To see this, refer to equations (4.35) and (4.42) where the fiscal externalities are zero under autarky since it holds for all t: $\partial r_t^j/\partial t_1^i = \partial r_t^j/\partial t_2^i = 0$ respectively $\partial r_t^j/\partial \Box^i = \partial k^j/\partial \Box^i = 0$ where $\Box = p_1, p_2, \rho$.

environmental taxes target the externality best and there is no role for capital taxation in this closed economy.

For the numerical simulations, I choose a logarithmic first-period utility function and a convex damage function such that equation (4.12) now reads:

$$W^i = ln(c_1^i) - \frac{1}{2}(r_1)^2 + \epsilon c_2^i \ . \tag{4.46}$$

For production, I use a standard CES function:

$$F(k_t^i, r_t^i) = \left[(k_t^i)^\alpha + (r_t^i)^\alpha\right]^{\frac{z}{\alpha}} \ , \tag{4.47}$$

where z describes the degree of homogeneity (for decreasing returns to scale $z < 1$), and the elasticity of substitution σ equals $1/(1-\alpha)$. That is, the lower is α, the more complementary are capital and resources. Note that for F_{kr} to be positive, $z > \alpha$ has to hold.[13]

The following two tables illustrate the results obtained for $n = 2$ and $Q^i \equiv 1$. The laissez-faire scenario involves no government intervention (all tax rates equal zero) which is obviously not an equilibrium. NE stands for a Nash equilibrium either without factor mobility, with only κ^i, only t_1^i and t_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. Equilibrium tax rates are written in brackets below the respective tax base. The displayed parameter constellations are just exemplary and chosen to highlight some effects. However, the derived results hold qualitatively also for all other constellations that I examined such that they are representative in a *pars pro toto* sense.

The ranking of these scenarios with respect to first-period resource use remains the same for all parameter constellations. Laissez-faire and Pareto-optimum describe the two extreme cases. The autarky NE always performs better than all NE with factor mobility since the environmental externality is not aggravated by factor mobility. Naturally, the NE with three instruments entails lower first-period resource use than the resource-taxes-only scenario which in turn outperforms the capital-tax-only NE.

Table 4.1 illustrates that the capital-tax-only policy is – as expected – not able to internalize much of the environmental externality, the reason being that this policy does not target the externality-generating input directly and is thus only an imperfect

[13] Strict quasi-concavity requires $\alpha < 1$ (Uzawa, 1962) which holds as I assume decreasing returns to scale.

	$\alpha = -5$				$\alpha = 0.5$			
	r_1^i (t_1^i)	r_2^i (t_2^i)	k^i (κ^i)	$p_1^{(i)}$ $\rho^{(i)}$	r_1^i (t_1^i)	r_2^i (t_2^i)	k^i (κ^i)	$p_1^{(i)}$ $\rho^{(i)}$
Laissez-faire	.893 (0)	.107 (0)	.113 (0)	.460 .491	.751 (0)	.249 (0)	1.913 (0)	1.182 .744
Pareto-opt.	.317 (0)	.683 (-2.814)	.029 (0)	.996 1.825	.257 (0)	.743 (-2.287)	1.277 (0)	1.815 .937
NE w/o mob.	.469 (0)	.531 (-2.083)	.093 (0)	.883 1.357	.366 (0)	.634 (-1.626)	1.443 (0)	1.571 .882
NE κ^i	.850 (0)	.150 (0)	.188 (-.485)	.512 .709	.714 (0)	.286 (0)	1.810 (.169)	1.206 .595
NE t_1^i, t_2^i	.469 (.883)	.531 (-.0006)	.093 (0)	.0003 1.357	.380 (.662)	.620 (-.313)	1.463 (0)	.885 .876
NE κ^i, t_1^i, t_2^i	.469 (.883)	.531 (-.0005)	.093 (.002)	.0002 1.356	.368 (.629)	.632 (-.342)	1.411 (.110)	.939 .780

Table 4.1: Simulation results for $z = 0.75$, $\bar{k} = 1$ and $\epsilon = 0.9$.

	$\alpha = 0.3$				$\alpha = 0.7$			
	r_1^i (t_1^i)	r_2^i (t_2^i)	k^i (κ^i)	$p_1^{(i)}$ $\rho^{(i)}$	r_1^i (t_1^i)	r_2^i (t_2^i)	k^i (κ^i)	$p_1^{(i)}$ $\rho^{(i)}$
Laissez-faire	.632 (0)	.368 (0)	2.361 (0)	2.602 2.427	.940 (0)	.060 (0)	.606 (0)	1.020 1.039
Pareto-opt.	.443 (0)	.557 (-4.434)	1.889 (0)	2.889 2.880	.257 (0)	.743 (-2.571)	.075 (0)	1.180 2.052
NE w/o mob.	.521 (0)	.479 (-2.606)	2.091 (0)	2.752 2.684	.379 (0)	.621 (-1.894)	.154 (0)	1.123 1.658
NE κ^i	.628 (0)	.372 (0)	2.346 (.046)	2.607 2.392	.934 (0)	.066 (0)	.579 (.076)	1.020 .971
NE t_1^i, t_2^i	.575 (.262)	.425 (-.437)	2.224 (0)	2.412 2.557	.541 (.418)	.459 (-.382)	.278 (0)	.660 1.389
NE κ^i, t_1^i, t_2^i	.524 (.189)	.476 (-1.218)	2.070 (.275)	2.559 2.414	.482 (.369)	.518 (-.263)	.046 (1.356)	.723 .805

Table 4.2: Simulation results for $z = 0.95$, $\bar{k} = 0.1$ and $\epsilon = 0.8$.

policy substitute for environmental taxes. Furthermore, our intuition is confirmed that a higher degree of complementarity between capital and resources makes a capital subsidy more likely.

For a high degree of complementarity, the private income externalities are relatively small such that first-period resource use nearly coincides in the autarky NE, the NE with environmental taxes only and the NE with all instruments. In the latter scenario, the capital tax is relatively small while for a higher degree of substitutability, the additional capital tax is higher and achieves a more significant reduction of first-period resource use relative to the NE with environmental taxes only. This can also be seen in Table 4.2 where the additional capital tax significantly lowers the interest rate and thus spurs second-period resource use through the capital-tax-interest-rate channel. This channel is the stronger, the higher is the elasticity of substitution. The following proposition summarizes these results.

Proposition 4.5 (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 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.*

4.6 Discussion

I have assumed perfect mobility of capital and resources. In reality, the degrees of mobility of the two factors might differ. Whereas the ease of resource transport depends, among others, on the distance between the trading partners, on the available infrastructure and the particular type of resource (coal, gas, oil etc.), capital may be more easily shifted around between countries. In the theoretical model, a higher degree of mobility would induce governments to lower the tax burden that it puts on this factor, because the marginal costs of tax increases are then perceived to be higher. Governments fear a reallocation of capital and resources to their disadvantage although in a symmetric equilibrium all governments set the same tax rates. This means that the more immobile production factor, resources, would be taxed at a higher rate and capital would be taxed at a lower rate than this model predicts.

Another important issue driving the results in the model is the degree of substitutability between capital and resources. As with all other things, I have assumed perfect foresight with respect to future technology. But, in fact, it may become (expectedly or unexpectedly) easier to substitute between these factors of production in the future. This is where innovation policy comes into play which may also be a policy instrument in interjurisdictional competition.

I have derived rather clear-cut results for the case that the substitution effect of a marginal change in the interest rate outweighs the income effect. For simplicity, I used a quasi-linear specification of the utility function. In the more general case, the income effect could exceed the substitution effect such that $\partial s/\partial \rho < 0$. Let us assume that Δ keeps its negative sign. If, for example, t_2^i marginally rises, then, in general equilibrium, the interest rate (still) falls due to a marginal change in t_2^i but resource prices may or may not rise as now $\Omega \gtreqless 0$. Due to the falling interest rate and the negative capital supply elasticity, the aggregate capital stock may rise. Consequently, firms may demand less or more (reversal of the Green Paradox) of the resource in the future, depending on the reaction of p_1 and p_2 which, in turn, hinges on the degree of complementarity. The effects of a marginal change in t_1^i on global resource use are now also ambiguous. The comparative statics of marginal changes in the capital tax, by contrast, can unambiguously be signed for $\Delta < 0$, independent of the elasticity of substitution: a marginal increase in κ^i leads to a decrease in the interest rate and thus, ceteris paribus, to a higher capital stock. Even for a very high elasticity of substitution, future aggregate resource use rises and pollution in the present falls. In addition to the effects described here, a generalization of preferences would encompass income effects on savings from changes in second-period taxes which do not show up under quasi-linear utility. To sum up, in the Nash equilibrium with all instruments, the change in the sign of $\partial s/\partial \rho$ may – at worst – change the signs of the tax rates such that we get a subsidy to capital and first-period resource use and a positive tax on second-period resource use. Subsidies on resource use can indeed be observed in many developing and emerging countries.

As a remedy to Green Paradox effects (as observed for a positive capital supply elasticity in this model), Sinn (2008) suggests a source-based tax on capital *income* earned by foreign resource owners in industrialized countries in order to flatten the extraction path of fossil resources. He argues in a partial equilibrium model that this tax would depress the net interest rate on reproducible capital and thus make it attractive for resource owners to leave more of the resource in situ. While a tax paid by resource suppliers (in the form of a cash flow tax, a unit tax on carbon extraction or an ad valorem sales tax) unfolds its effects on the extraction path through its change over time, a capital income tax as proposed by Sinn would tilt the extraction path in the right direction as long as it has a positive sign.[14] In my model, the instrument most similar to the proposed tax on capital income is the tax on investment, i.e., capital *use*, which is also source-based. This tax, however, is incurred by the firms that rent capital on the global market and thus does not affect capital income directly. In contrast to supply-side policies as defined by Sinn (2008), all tax rates employed in this model exert their influence on the extraction path through the *demand-side* for capital and resources.

Finally, the open-loop Nash equilibrium is time-inconsistent as governments would deviate from their announced future policies once the second period has arrived. The reason is that the environmental externality which results from first-period resource use cannot be addressed anymore by means of second-period policies. This time-inconsistency can be addressed by taxing savings in the first period instead of second-period investment since in symmetric equilibrium these taxes are equivalent. The tax on (or subsidy to) savings would as well influence the interest rate in the second period and could thus be used to induce substitution out of capital towards resources in the second period which, in turn, slows down resource extraction. Furthermore, the time-inconsistency is mitigated by the fact that the capital tax raises revenue in the second period while the resource tax is negative. This implies, compared to a no-tax policy in the second period, some redistribution from capital to resources in the second period. As this redistribution primarily affects production firms, credibly announced earmarking of capital tax revenue to resource subsidization would alleviate the time-inconsistency problem although it is unlikely that tax revenues and subsidies net each other out in equilibrium.

4.7 Conclusion

I have analyzed strategic tax-setting of governments competing for mobile resources and mobile capital in a general equilibrium model. I found that unilateral policies are effective in slowing down resource extraction. Green Paradox effects arise with a positive capital supply elasticity. 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

[14] Jaakkola (2012) finds 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 whenever this country does not produce goods. By contrast, van der Meijden et al. (2014) are able to show in a general equilibrium framework that a tax on the resource-exporting country's capital income may actually accelerate resource extraction.

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 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 as 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, future research may explore asymmetries with respect to resource or capital endowment. An asymmetric setting incorporates the incentive for resource-importing countries to tax away Hotelling rents from resource exporters. It would also be interesting to examine time-consistent policies in this setting.

4.8 Appendix

Derivation of comparative statics

Totally differentiating the first-order conditions (4.3)–(4.5) for all $i = 1, \ldots, n$ yields:

$$f_{rr} dr_1^i - dt_1^i = dp_1 \ , \tag{4.A.1}$$

$$F_{kr} dk^i + F_{rr} dr_2^i - dt_2^i = dp_2 \ , \tag{4.A.2}$$

$$F_{kk} dk^i + F_{kr} dr_2^i - d\kappa^i = d\rho \ . \tag{4.A.3}$$

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 (4.A.1)–(4.A.3) for dr_1^i, dr_2^i and dk^i, we obtain:

$$dr_1^i = \frac{1}{f_{rr}} (dp_1 + dt_1^i) \ , \tag{4.A.4}$$

$$dr_2^i = \frac{F_{kk}}{\Gamma} \left[dp_2 + dt_2^i - \frac{F_{kr}}{F_{kk}} (d\rho + d\kappa^i) \right] \ , \tag{4.A.5}$$

$$dk^i = \frac{F_{rr}}{\Gamma} \left[d\rho + d\kappa^i - \frac{F_{kr}}{F_{rr}} (dp_2 + dt_2^i) \right] \ . \tag{4.A.6}$$

Denoting $w_1^i = \pi_1^i + \Pi_1^i + \tau_1^i$, we have:

$$dw_1^i = p_1 (dq_1^i - dr_1^i) + f_r dr_1^i \ , \tag{4.A.7}$$

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:

$$\sum_{l=1}^{n} (dq_1^l - dr_1^l) = 0 \ . \tag{4.A.8}$$

Totally differentiating Hotelling's rule (4.7) and the capital and resource market equilibrium conditions (4.16) and (4.17), using (4.A.7) and (4.A.8), yields:

$$dp_2 = (1 + \rho) dp_1 + p_1 d\rho \ , \tag{4.A.9}$$

$$\sum_{l=1}^{n} dk^l = \sum_{l=1}^{n} \frac{\partial s^l}{\partial \rho} d\rho + \sum_{l=1}^{n} \frac{\partial s^l}{\partial w_1^l} dw_1^l = \sum_{l=1}^{n} \frac{\partial s^l}{\partial \rho} d\rho + \sum_{l=1}^{n} f_r dr_1^l \ , \tag{4.A.10}$$

$$\sum_{l=1}^{n} dr_1^l = - \sum_{l=1}^{n} dr_2^l \ . \tag{4.A.11}$$

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

$$\frac{nf_r}{f_{rr}}dp_1 + \frac{nF_{kr}}{\Gamma}dp_2 - \frac{n\left[F_{rr} - \frac{\partial s}{\partial \rho}\Gamma\right]}{\Gamma}d\rho + \sum_{l=1}^{n}\frac{f_r}{f_{rr}}dt_1^l + \sum_{l=1}^{n}\frac{F_{kr}}{\Gamma}dt_2^l - \sum_{l=1}^{n}\frac{F_{rr}}{\Gamma}d\kappa^l = 0 \ , \tag{4.A.12}$$

$$\frac{n}{f_{rr}}dp_1 + \frac{nF_{kk}}{\Gamma}dp_2 - \frac{nF_{kr}}{\Gamma}d\rho + \sum_{l=1}^{n}\frac{1}{f_{rr}}dt_1^l + \sum_{l=1}^{n}\frac{F_{kk}}{\Gamma}dt_2^l - \sum_{l=1}^{n}\frac{F_{kr}}{\Gamma}d\kappa^l = 0 \ , \tag{4.A.13}$$

Finally, by inserting (4.A.9) into (4.A.12) and (4.A.13), it follows:

$$\frac{(1+\rho)F_{kr}}{\Gamma}dp_1 - \frac{F_{rr} - \frac{\partial s}{\partial \rho}\Gamma - p_1F_{kr}}{\Gamma}d\rho - \frac{1}{n}\left[\sum_{l=1}^{n}\frac{F_{rr}}{\Gamma}d\kappa^l - \sum_{l=1}^{n}\frac{F_{kr}}{\Gamma}dt_2^l\right] = 0 \ , \tag{4.A.14}$$

$$\frac{\Gamma + (1+\rho)f_{rr}F_{kk}}{F_{rr}\Gamma}dp_1 + \frac{p_1F_{kk} - F_{kr}}{\Gamma}d\rho + \frac{1}{n}\left[\sum_{l=1}^{n}\frac{1}{f_{rr}}dt_1^l + \sum_{l=1}^{n}\frac{F_{kk}}{\Gamma}dt_2^l - \sum_{l=1}^{n}\frac{F_{kr}}{\Gamma}d\kappa^l\right] = 0 \ . \tag{4.A.15}$$

These two equations jointly determine the market reactions $dp_1/d\Box^i$ and $d\rho/d\Box^i$ to unilateral marginal increases in $\Box = t_1, t_2, \kappa$ in country i, where a unilateral increase in t_1^i, for example, is found by setting $dt_2^i = d\kappa^i = 0$ and $dt_1^k = dt_2^k = d\kappa^k = 0$ for all $k \neq i$. Inserting these results into (4.A.9) implies $dp_2/d\Box^i$.

Plugging the market reactions as described by (4.18a)–(4.18c) and (4.21a)–(4.21c) back into (4.A.4)–(4.A.6) for the tax-increasing country i and country $j \neq i$, we obtain after some rearrangements equations (4.19a)–(4.20c) and (4.22a)–(4.23f).

Proof of Lemma 4.1

We know that aggregate resource use in the first period is – for given taxes in all other countries – a function of t_1^i and t_2^i. Totally differentiating $r_1 = G(t_1^i, t_2^i)$ yields:

$$dr_1 = \frac{\partial G}{\partial t_1^i}dt_1^i + \frac{\partial G}{\partial t_2^i}dt_2^i \ . \tag{4.A.16}$$

We also know from the comparative statics that

$$\frac{\partial r_1}{\partial t_1^i}\Big|_{dt_2^i=0} = -(1+\rho)\frac{\partial r_1}{\partial t_2^i}\Big|_{dt_1^i=0} \ . \tag{4.A.17}$$

From these two equations follows immediately:

$$\frac{\partial G}{\partial t_1^i} = -(1+\rho)\frac{\partial G}{\partial t_2^i} \quad \Leftrightarrow \quad \frac{\partial G}{\partial t_1^i} + (1+\rho)\frac{\partial G}{\partial t_2^i} = 0 \ , \tag{4.A.18}$$

which is a partial differential equation.
Let $G(t_1^i, 0) = G(t_1^i)$ for $t_2^i = 0$. If $G(t_1^i)$ exists and $G(t_1^i)$ differentiable, then it follows from the calculus of partial differential equations:

$$G(t_1^i, t_2^i) = G\left(t_1^i - \frac{t_2^i}{1+\rho}\right) . \tag{4.A.19}$$

That is, aggregate first-period resource use and thus pollution only depend on the difference $t_1^i - t_2^i/(1+\rho)$. □

Comparative statics of marginal increases in r_1^i

To obtain the equilibrium effects of increases in r_1^i on world market prices, set all marginal tax changes in equations (4.A.4)–(4.A.6) to zero but note that r_1^i does not depend on p_1 here. While (4.A.9) still applies, the differentiated market equilibrium conditions read:

$$\sum_{l=1}^{n} dk^l = \sum_{l=1}^{n} \frac{\partial s^l}{\partial \rho} d\rho + f_r dr_1^i + \sum_{\substack{l=1 \\ l \neq i}}^{n} f_r dr_1^l \ , \tag{4.A.20}$$

$$r_1^i + \sum_{\substack{l=1 \\ l \neq i}}^{n} dr_1^l = -\sum_{l=1}^{n} dr_2^l \ . \tag{4.A.21}$$

Starting from a symmetric equilibrium where $dr_t^l = dr_t^j$ and $dk^l = dk^j$ for all t and $l, j \neq i$, and inserting (4.A.4)–(4.A.6) and (4.A.9) into (4.A.20) and (4.A.21) for all $l \neq i$, we obtain:

$$\frac{\partial \rho}{\partial r_1^i} = \frac{(1+\rho) f_{rr} \left[(p_1 F_{kk} - F_{kr})(f_r F_{kk} - F_{kr}) - (1+\rho) f_{rr} F_{kk} \Omega\right]}{(p_1 F_{kk} - F_{kr}) \left[(n-1)\Delta - n(1+\rho) f_{rr} \Omega\right]} < 0 \ , \tag{4.A.22}$$

$$\frac{\partial p_1}{\partial r_1^i} = -\frac{f_{rr} \Delta}{(n-1)\Delta - n(1+\rho) f_{rr} \Omega} > 0 \ , \tag{4.A.23}$$

$$\frac{\partial p_2}{\partial r_1^i} = \frac{(1+\rho) f_{rr} \left[(p_1 F_{kk} - F_{kr})(f_r F_{kr} - \Phi) - (1+\rho) f_{rr} F_{kr} \Omega\right]}{(p_1 F_{kk} - F_{kr}) \left[(n-1)\Delta - n(1+\rho) f_{rr} \Omega\right]} > 0 \ . \tag{4.A.24}$$

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