Strategic interactions in climate policy*

Cecilie Marie Løchte Jørgensen† Frederik Læssøe Nielsen§

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PRELIMINARY WORK - PLEASE DO NOT CIRCULATE OR CITE

Abstract

We investigate strategic interaction in climate actions in a two-country model with integrated capital and goods markets. We find that there is a free-riding issue in the abatement dimension of policy, but that, contrary to common perception, there might be strategic complementarity in the taxation dimension. When trading partners increase their climate tax, it induces a free-riding incentive, as pointed out in the climate literature, but a less fierce tax competition also makes it less costly to raise public funds domestically. Our results show that the green transition may be easier than predicted, as climate actions, at least in the tax dimension, may very well reinforce each other.

Keywords: Strategic interaction, carbon taxes, climate change, non-cooperative policy

JEL Classification: C72; F18; H23; Q58.

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†Labour and Public Policy, Department of Economics and Business Economics, Aarhus University, Fuglesangs Alle 4, 8210 Aarhus V, Denmark. Phone: +45 8716 5576. Email: clj@econ.au.dk. Corresponding author.

§Labour and Public Policy, Department of Economics and Business Economics, Aarhus University, Fuglesangs Alle 4, 8210 Aarhus V, Denmark. Email: fln@econ.au.dk.

1 Introduction

The world is in a deadlock. No country wants to move first in solving the climate crisis. Why would any country impose carbon taxes or spend money on abatement when the rest can just free ride? When asking such a question, one implicitly assumes that climate actions are strategic substitutes, implying that when one country strengthens its climate actions, it is optimal for others to free ride and weaken theirs.

But can we be sure that free riding is, in fact, the optimal policy response to a trading partner increasing its efforts against climate change? In this paper, we investigate whether home and foreign carbon taxes and abatement expenditures are unquestionably strategic substitutes or whether we could imagine a world where they are strategic complements. The terminology of strategic substitutability and complementarity was first introduced by Bulow et al. (1985) and subsequently by Cooper and John (1988). They define strategic substitutes as policy actions that are mutually negating, meaning that - using taxes as an example - when one country raises its tax, the other country is induced to lower theirs. Strategic complements are, oppositely, policy actions that are mutually reinforcing, meaning that when one country increases its tax, the other country is induced to increase its tax as well.

First, we make a stylised theoretical model to highlight the important mechanisms that pull towards either strategic complementarity or substitutability. Several effects are at play: First, countries compete for economic activity, and thus, tax base. This implies that if a trading partner increases its tax rate, the tax competition becomes less fierce, leaving more room to increase your own taxes. This channel gives rise to strategic complementarity. Note that, similar arguments are often used to explain why countries meet tax cuts among trading partners with tax cuts of their own. Secondly, when one country increases its climate actions, the marginal benefit for the other country to do the same decreases. This channel gives rise to strategic substitutability. In the tax dimension, the different effects lead to ambiguity of the total effect of a trading partner increasing its climate tax. Contrary to this, we show that abatement expenditures are unambiguously strategic substitutes. This is so, as an increase in the abatement share induces only the free-riding effect but does not affect the competition for economic activity.

The stylised model merely serves to illustrate the different effects in the larger-scale model, that we solve numerically. Importantly, the stylised model does not incorporate interdependencies from international trade or fully integrated capital markets - features we include in our larger-scale, main model. Nonetheless, it serves to illustrate the main argument for why assuming strategic substitutability in climate policy is potentially not such an innocent assumption as one might think. In the numerical part of the paper, we build a multi-country general equilibrium model with integrated capital and goods markets and a shared climate where policymakers unilaterally choose taxation and abatement spending strategies. The richer model allows us to take into account the above-mentioned effects as well as general equilibrium effects on e.g. wages. We solve for best response functions numerically to assess whether green policy actions are strategic complements or, as often assumed in the literature, strategic complements.

We investigate different ways for the governments to spend their tax revenues. They spend revenues on either climate abatement or public welfare. Whereas investments in public welfare only benefit people in the investing country, investments in abatement benefit the entire world because the state of the climate is a world-wide public good. In our main specification, where governments spend their tax revenues entirely on public spending (approximating the world as it is today), we find that climate taxes are actually strategic complements. We find that the higher the abatement budget share of the government is, the flatter is the best response function and at some point the slope turns negative, implying strategic substitutability. In line with our theoretical predictions, abatement expenditures are always strategic substitutes.

Compared to the binary prisoners-dilemma types of models that inevitably foster bang-bang decision rules, treating policy as choices on a continuum, allows us to take these mechanisms into account, and thus, add more nuance to the climate-policy question. Regardless of methodological approach, there is general consensus in the literature that a uniform carbon tax across countries is the most efficient climate change mitigation strategy (e.g. Perdana, Tyers, et al. 2017; Weitzman 2014). But in the absence of worldwide uniform policies, the picture becomes less clear. Perdana, Tyers, et al. (2017) compare carbon taxes and free riding in a multi-country computable general equilibrium (CGE) model and show that all countries/regions should optimally free ride in climate policies except for China, the US, and the EU. Nordhaus (2015) shows that no cooperative climate equilibria exist. But when including penalties for free riding, it is possible to construct large climate cooperations. Other papers have extended on the idea of climate clubs (Sælen 2016; Hovi et al. 2020). Sælen (2016) investigate whether side payments ensure stability of the climate coalition, where Hovi et al. (2020) more generally look at conditions for stability - e.g. conditional participation. Common for their methodological approaches is the focus on the binary choice of whether to abate or not. We divert from the binary choice models and consider the non-cooperative case in a continuous setting. Even though, the literature generally talks about climate abatement as a binary coordination problem (see e.g. DeCanio and Fremstad (2013)), in reality it is a continuous problem with more options than "cooperate" and "defect". Our model contains no clubs or sanctions, only countries that act in their own best interests. But even in this case, it is not trivial how countries strategically interact in their choices of climate policies.

There has been extensive research on strategic interactions with different types of taxes. But the question whether climate taxes are strategic complements or substitutes is still new. Climate taxes are different because the inclusion of the climate in any economic model adds another layer (as introduced by Nordhaus (2015) in the DICE model). How to incorporate the climate in an economic model is not trivial: Either the climate has to influence production or agents need to get utility from the climate. We choose the second approach, and thus, agents and policymakers have an extra dimension in their decision making, in the sense that the state of the climate matters for welfare.

In that vein, many rich, primarily European, countries begin to form stronger preferences for combating climate changes. Despite this, it seems to be an empirical fact that global coordination of climate policies is slow. Many countries are eager to take climate action but are reluctant to do so unilaterally because of free-riding concerns. Therefore, it seems more relevant than ever to nuance and shed light on the validity of the free-riding argument. If the free-riding motive is dominated by competing effects such that green taxes are strategic complements, it would significantly ease the transition toward a greener world as it implies that countries optimally double down on the choices taken by first-movers.

2 Theory

In this section, we present a stylised two-country model with possibilities of leakage of production because of different environmental tax rates. Social welfare is determined by private and public consumption and abatement initiatives which ensure a better climate. We investigate analytically, which mechanisms are at play before we move on to a richer model in the numerical part of the paper.

2.1 Model

Consider a domestic economy where output is determined solely by the environmental tax rates in the home and the foreign country

$$y = f\left(\tau, \tau^f\right).$$

Domestic output is decreasing in the home tax rate, τ, and increasing in the foreign tax rate, τ^f. We equip variables specific to the foreign country with a superscripted f. Households consume the fraction of production they have left after paying taxes,

$$c = (1-\tau)\cdot y.$$

The government spends a fraction, μ, of the tax revenue on abatement expenditures, A,

$$A = \mu \cdot \tau \cdot y,$$

and the remaining part of the tax revenue on a public good, g,

$$g = (1-\mu)\cdot \tau \cdot y.$$

Similar private and public budget constraints exist in the foreign country.

Social welfare is given by the utility of consumption, the public good, and disutility from emissions. The last term consists of emissions which are proportional to output subtracted abatement which is a function, $\psi(\cdot)$, of abatement expenditures, A. Importantly, agents get utility from both home and foreign emissions and abatement, which highlights that the climate is a worldwide public good.

$$\Omega = u(c) + v(g) - h\left(y - \psi\left(A\right) + y^f - \psi\left(A^f\right)\right).$$

where $u', v', h' > 0$ and $u'', v'' < 0$, $h'' > 0$.

2.2 Analysis

We are interested in knowing if the home country raises or decreases its tax rate/abatement expenditures in response to the foreign country raising theirs. Specifically that is, we are interested in the signs of $\frac{\partial \tau^f}{\partial \tau}$ and $\frac{\partial \mu^f}{\partial \mu}$. In case of only *one* policy variable (by treating the other as exogenously given), the analysis is somewhat simple. By total differentiation of the first-order condition of the policymaker, it is possible to show that

$$\text{sign}\left(\frac{\partial \tau^f}{\partial \tau}\right) = \text{sign}\left(\Omega_{\tau^f \tau}\right)$$

and

$$\text{sign}\left(\frac{\partial \mu^f}{\partial \mu}\right) = \text{sign}\left(\Omega_{\mu^f \mu}\right).$$

If we allow for the governments to decide on both policy variables in each country at the same time, the analysis becomes more tedious. Here, the countries can adjust both their tax rate and abatement expenditures in response to a foreign policy change, and then we have that e.g.

$$\text{sign}\left(\frac{d\tau}{d\tau^f}\right) = \text{sign}\Big(\Omega_{\tau\mu}\Omega_{\mu\tau^f} - \Omega_{\tau\tau^f}\Omega_{\mu\mu}\Big)\,. \tag{1}$$

See Appendix B.2 for the derivations.

2.3 One-policy-variable case

In this section, we start by looking at the one-policy-variable case. First, we hold relative abatement expenditures constant and look at the tax rates. Assuming that countries don't cooperate, the social planner solves the optimisation problem taking the foreign tax rate as given. This yields a first-order condition:

$$\begin{aligned}\Omega_\tau =& u_c\left(\cdot\right)\left[\left(1-\tau\right) f_\tau - f\right] + (1-\mu) v_g\left(\cdot\right)\left[f + \tau f_\tau\right] \\ &-h_E\left(\cdot\right)\underbrace{\left[f_\tau - \mu\psi_A\left(\cdot\right)\left[f+\tau f_\tau\right] + f^f_\tau - \mu^f \tau^f f^f_\tau \psi_A\left(\cdot\right)\right]}_{\equiv \Lambda < 0} = 0.\end{aligned}$$

We also have the standard second-order condition, $\Omega_{\tau\tau} < 0$ which we assume to hold. By total differentiation of the first-order condition, we get:

$$\begin{aligned}\Omega_{\tau\tau^f} =& \underbrace{(1-\mu)v_g(\cdot)\,f_{\tau^f}}_{1.} + \underbrace{h_E(\cdot)\left[\mu\psi_A(\cdot)\,f_{\tau^f} + \mu^f f^f_\tau \psi_A(\cdot)\right]}_{2.} - \underbrace{u_c(\cdot)\,f_{\tau^f}}_{3.} \\ & - \underbrace{h_{EE}(\cdot)\left[f_{\tau^f} + f^f_{\tau^f}\right]\Lambda}_{4.} + \underbrace{h_{EE}(\cdot)\,\psi_A(\cdot)\left[\mu^f\left[f^f + \tau^f f^f_{\tau^f}\right]\right]\Lambda}_{5.} \\ & + \underbrace{u_{cc}(\cdot)\left[(1-\tau)\,f_{\tau^f}\right]\left[(1-\tau)\,f_\tau - f\right] + (1-\mu)v_{gg}(\cdot)\left[(1-\mu)\tau f_{\tau^f}\right]\left[f+\tau f_\tau\right] + h_{EE}(\cdot)\psi_A(\cdot)\left[\mu\tau f_{\tau^f}\right]\Lambda}_{6.} \lesseqgtr 0.\end{aligned}$$

Note that, $h_A(\cdot)$ and $v_g(\cdot)$ cancel in optimum. Furthermore, we assume that $y_{\tau^f\tau} = 0$.[1] The sign of the expression (and consequently also the sign of $\frac{\partial \tau^f}{\partial \tau}$) is ambiguous because several mechanisms are at play. First, we have two effects that pull towards strategic complementarity:

1. With a higher foreign tax, the marginal benefit of increasing the home tax in terms of public consumption is larger, because the tax base is larger.

2. With a higher foreign tax, competition for production is less fierce and therefore it is less costly to raise the tax (tax competition effect). Also, with a higher foreign tax, the tax base in the home country is larger and therefore an increase in the tax will yield relatively more public consumption (tax base effect). There is a mitigating effect when the foreign country spends its revenue on abatement because it is less costly to raise the tax/lose production when some of it is spent on a worldwide public good.

Secondly, we have three effects which pull towards strategic substitutability

3. With a higher foreign tax, it is relatively more expensive (in terms of private consumption) to raise the tax for the home country because the tax base is larger. You simply lose more by increasing the tax when you have more to begin with.

[1] We make this simplifying assumption to cut down on the number of mechanisms that are at play when countries choose their tax rates. Often, one assumes that $y_{\tau^f\tau} > 0$ such that the higher the foreign tax rate, the smaller is the effect of the domestic tax rate on production. This condition captures that the leakage effects of increased environmental taxes are less severe, if the rest of the world is less compelling to relocate to for producers.

4. With a higher foreign tax, total world production is smaller (leakage is less than 1) and thus total world emissions are smaller. This decreases the marginal utility of abatement and thus makes it less attractive for the home country to raise its tax.

5. With a higher foreign tax, the foreign country abates more. This reduces the marginal utility of abatement for the home country and thus the incentive to increase the tax (free-riding effect).

Lastly, we have the sixth effect which is the ambiguous tax base effect: The home country has a larger tax base when the foreign country raises its tax because of leakage.

6. With a higher foreign tax, production in the home country is higher. For a given home tax rate, private consumption is higher and marginal utility of private consumption is thus lower. All else equal, this will induce the home country to raise the tax as private consumption is less attractive. Similarly, a larger home production and thereby public consumption implies a lower marginal utility of public consumption which gives incentives to lower the tax.[2] Last, with a larger tax base, abatement increases in the home country. This reduces the marginal utility of abatement and induces the home country to lower its tax.

It is clear from the above that even in a stylised model with only one policy variable and without important features such as international trade and integrated capital markets, several effects work simultaneously and in different directions. We have the tax base effect, which pulls in different directions, tax competition which pulls towards strategic complementarity of the tax rates, and then we have the free-riding effect, which unambiguously pulls towards strategic substitutability. Next, we have an example, where the free-riding effect is the only effect at play. This is the case, when we look at the strategic relationship between abatement expenditures in the two countries, μ and μ^f, by looking at the sign of $\frac{d\mu}{d\mu^f}$. Again, we know that $\text{sign}\left(\frac{d\mu}{d\mu^f}\right) = \text{sign}\left(\Omega_{\mu\mu^f}\right)$ if we assume exogenous tax rates and thus we look at the second derivative of the social welfare function and find

$$\Omega_{\mu\mu^f} = -h_{EE}\left(\cdot\right)\psi_A\left(A\right)\left[\tau f\right]\psi_A\left(A^f\right)\left[\tau^f f^f\right] < 0$$

[2]We assume that $\frac{\partial(f\cdot\tau)}{\partial\tau} = f + \tau \cdot f_\tau > 0$. Else it would imply that we were on the wrong part of the Laffer curve such that the domestic tax revenue would be decreasing in τ.

From the properties of the utility function, the abatement function, and the production function, we see that the expression is unambiguously negative, implying strategic substitutability in abatement expenditures. Here, we see a direct example of the free-riding effect. When the other country raises its contribution to solve the climate problem, your marginal benefit from doing the same decreases while at the same time, your marginal benefit from getting more public consumption is unaffected, inducing you to shift from abating the climate to spend money on general public spending.

Of course, it would also be possible to investigate the signs of $\Omega_{\mu\tau^f}$ and $\Omega_{\tau\mu^f}$. See Appendix B.1.

2.4 Two-policy-variables case

In the previous section, we looked at the mechanisms at play in the model under the assumption that each country only had one policy variable. Of course, it is also relevant to look at a scenario where the policy-maker chooses both the tax rate and abatement expenditures. Making this analysis would require us to look at Equation (1) and inserting four partial derivatives. The effects at play are the same as presented in the one policy-variable case and they don't boil down to anything more nice or intuitive. Thus, we will leave the two policy-variables case for now, knowing which mechanisms are at play. In the numerical part of the paper, we will return to this case and show simulations that highlight which effects dominate.

2.5 Spillovers

Until now, we have only looked at the non-cooperative solution to the social planner's problem, meaning that the social planner has optimised without any coordination with the other country. It is, however, informative to look at the cooperative solution which we will do now.

2.5.1 Tax Rate

In the cooperative game, the social planner chooses the tax rate that maximises joint utility of the two countries, $\Omega_{\tau}\left(\cdot\right) + \Omega_{\tau^f(\cdot)}$. We call the corresponding cooperative tax rate, τ_c, which has the following first-order condition:

$$\frac{\partial \Omega^c}{\partial \tau} = \Omega_\tau(\cdot) + \Omega_{\tau^f}(\cdot) = 0.$$

When we evaluate this condition in the non-cooperative equilibrium, we find:

$$\frac{\partial \Omega^c}{\partial \tau}|_{\tau=\tau^{NC}} = \Omega_{\tau^f}(\cdot)$$

Inserting into the expression to look at $\Omega_{\tau^f}(\cdot)$, we get:

$$\begin{aligned}\Omega_{\tau^f}(\cdot) =& u_c(\cdot)(1-\tau) f_{\tau^f} + (1-\mu)\tau f_{\tau^f} v_g(\cdot) \\ & - h_E(\cdot)\left[f_{\tau^f} - \psi_A(A)\mu\tau f_{\tau^f} + f^f_{\tau^f} - \psi_A\left(A^f\right)\mu^f\left[f^f + \tau^f f^f_{\tau^f}\right]\right] > 0\end{aligned}$$

The expression is unambiguously positive, which implies that there are positive spillovers from increasing the tax rate and that the cooperative tax is higher than the non-cooperative / unilaterally chosen tax rate. Thus, in the non-cooperative equilibrium, policymakers choose a tax rate that is too low from the perspective of a cooperative social planner.

2.5.2 Abatement expenditures

When we do the exact same exercise for abatement expenditures, we find

$$\frac{\partial \Omega^c}{\partial \mu}|_{\mu=\mu^{NC}} = \Omega_{\mu^f}(\cdot) = h_E(\cdot)\psi_A\left(A^f\right)\tau^f f^f > 0$$

Again, the expression is unambiguously positive, meaning that there are positive spillovers associated with increasing the share spent on abatement, μ. Thus, the cooperative share of abatement is higher than the unilaterally chosen share.

3 Model

In this section, we present the two-country, two generations OLG model with integrated capital and goods markets, greenhouse gas emissions caused by the production of consumption goods, and atomistic agents who consume without internalising the negative climate externalities related to the production of goods. Policymakers in the two countries design climate policies unilaterally and spend the revenues from green taxes on a general public sector or abatement of national greenhouse gasses.

3.1 Individuals

Individuals reside in either of two countries: *Home* (H) or *Foreign* (F) and live for two periods. We use index $i = H, F$ to refer to the two countries and denote young and old individuals with superscripts y and o.

The number of individuals in a cohort in country i at time t is given by N_t^i. Each young individual inelastically supplies one unit of labour, while an old individual inelastically supplies R units of labour. Total labour supply in country i is denoted by L_t^i and is allocated between the two production sectors (x and y) and the government sector (denoted by superscript g) in country i such that:

$$L_t^i = (1+R)N_t^i = L_t^{i,x} + L_t^{i,y} + L_t^{i,g}.$$

The fraction of old age spent working, R, is exogenous to the individual. Therefore, $1+R$ can be interpreted as a mandatory retirement age. Individuals are atomistic, implying that they can affect neither factor nor goods prices. They maximise lifetime utility subject to standard first- and second-period budget constraints. The problem can be analysed as two separate problems; an intertemporal and an intratemporal decision. They choose how much to save from young to old (the intertemporal problem) and how much of good x relative to good y they want to consume (the intratemporal problem). The intertemporal problem looks as follows

$$\max_{s_t^i} \quad U_t^i = \frac{\left(c_{y,t}^i\right)^{1-\theta_c} - 1}{1-\theta_c} + \omega_g \cdot \frac{\left(g_t^i\right)^{1-\theta_g} - 1}{1-\theta_g} - \omega_E \cdot E_t^\gamma$$
$$+\beta \left[\frac{\left(c_{o,t+1}^i\right)^{1-\theta_c} - 1}{1-\theta_c} + \omega_g \cdot \frac{\left(g_{t+1}^i\right)^{1-\theta_g} - 1}{1-\theta_g} - \omega_E \cdot E_{t+1}^\gamma \right]$$

s.t.

$$c_{y,t}^i = (1-\tau_l) \cdot w_t^i - s_t^i,$$
$$c_{o,t+1}^i = (1-\tau_l) \cdot R \cdot w_{t+1}^i + (1+r_{t+1}^i)s_t^i$$

Individuals discount old-age utility with β. They get utility from consumption of a composite good, c, and government spending, g. They get disutility from the stock of greenhouse gas emissions, E. The damage function is similar to the one in Weitzman (2010), where the damage of emissions are convex, implying that the marginal damage of emissions is increasing.

Consumption, c, is a composite good which is a CES-aggregate of x and y

$$c_t^i = c\left(x_t^i, y_t^i\right) = \left((\varphi)^{\frac{1}{\epsilon}} \left(x_t^i\right)^{\frac{\epsilon-1}{\epsilon}} + (1-\varphi)^{\frac{1}{\epsilon}} \left(y_t^i\right)^{\frac{\epsilon-1}{\epsilon}} \right)^{\frac{\epsilon}{\epsilon-1}}$$

where $x_t^i = x_t^{i,H} + x_t^{i,F}$ is the consumption of good x in country i at time t, and $y_t^i = y_t^{i,H} + y_t^{i,F}$ is the consumption of good y in country i at time t. Note that we suppress the generation index, and that x (y) goods produced in country H, $x_t^{i,H}$ ($y_t^{i,H}$), and x (y) produced in F, $x_t^{i,F}$ ($y_t^{i,F}$), are perfect substitutes, implying that the individual consumes from whichever country is cheaper. We refer to x as a low-polluting good and y as a high-polluting good. More details on that in Section 3.2. We let ϵ denote the elasticity of substitution between good x and y. The weights, ω_g and ω_E, in the utility function represent the weights of government spending and the state of the climate, measured by the emission stock, relative to consumption.

Regarding the first- and second-period budget constraints, the wage, w, is taxed with a proportional income tax, τ_l, s_t^i denotes saving in period t, and $(1 + r_{t+1})\, s_t^i$ is the capital income earned on the previous period's savings. The budget constraints are stated in terms of the composite good, and similarly, individuals save in the composite good as well.

Solving the intertemporal problem yields the standard Euler equation for consumption:

$$\left(c_{y,t}^i\right)^{-\theta_c} = \left(1 + r_{t+1}^i\right) \cdot \beta \cdot \left(c_{o,t+1}^i\right)^{-\theta_c}.$$

To find the allocation between x and y, we solve the following intratemporal problem: Consider an individual that owns one low-polluting good. The individual maximises the amount of composite goods that can be bought for the low-polluting good. Individuals maximise over low- and high-polluting goods and face the following problem

$$\begin{aligned} \max_{x,\,y} \quad & c\,(x, y) = \left(\varphi^{\frac{1}{\epsilon}} x^{\frac{\epsilon-1}{\epsilon}} + (1-\varphi)^{\frac{1}{\epsilon}}\, y^{\frac{\epsilon-1}{\epsilon}}\right)^{\frac{\epsilon}{\epsilon-1}} \\ \text{s.t.} \quad & x + py = 1 \end{aligned}$$

where p is the relative price of y relative to x. Evaluating in optimal quantities, we get $\pi \coloneqq c\,(x^*, y^*)$ which is the maximum amount of composite goods that can be obtained from one x, thus pinning down the relative price between low-polluting and composite goods. Note that the homotheticity of the aggregator implies that x and y are consumed in constant proportions given the relative price p, irrespective of the income of the individual, thus allowing us to pin down a π that is independent of income. See Appendix A for a derivation of the analytical expression for π.

3.2 Firms

Firms in both countries produce according to identical Cobb-Douglas production functions with decreasing returns to scale:

$$x_t^{s,i} = \left(K_t^{x,i}\right)^{\alpha_x \rho} \left(L_t^{x,i}\right)^{(1-\alpha_x)\rho}$$
$$y_t^{s,i} = \left(K_t^{y,i}\right)^{\alpha_y \rho} \left(L_t^{y,i}\right)^{(1-\alpha_y)\rho},$$

where superscript s denotes supply. Both goods are produced with capital, K, and labour, L, but the weights on the inputs, α_x and α_y, are different. To capture that y pollutes more than x, we impose $\alpha_x < \alpha_y$ as capital is the polluting factor of production in our setup. We choose a production function with decreasing returns to scale to avoid indeterminacy or corner solutions with complete specialisation. Having $\rho < 1$ captures the degree of decreasing returns to scale.

Firms in country i operating in sector x (similar for sector y) maximise profits taking prices of labour and capital as given

$$\max_{L_t^{i,x},\ K_t^{i,x}} \quad \pi_t x_t^{s,i} - w_t^i L_t^{i,x} - r_t^{i,x} K_t^{i,x}$$

Firms face perfectly competitive factor markets and, therefore, pay factors according to the values of their effective (after depreciation and tax) marginal products as measured in composite goods.

$$r_t^{i,x} = \left(\pi_t \cdot \frac{\partial F^x\left(K_t^{i,x}, L_t^{i,x}\right)}{\partial K_t^{i,x}} - \delta\right) \cdot (1 - \tau_i)$$
$$r_t^{i,y} = \left(\pi_t \cdot p_t \cdot \frac{\partial F^y\left(K_t^{i,y}, L_t^{i,y}\right)}{\partial K_t^{i,y}} - \delta\right) \cdot (1 - \tau_i)$$
$$w_t^{i,x} = \pi_t \cdot \frac{\partial F^x\left(K_t^{i,x}, L_t^{i,x}\right)}{\partial L_t^{i,x}}$$
$$w_t^{i,y} = \pi \cdot p_t \cdot \frac{\partial F^y\left(K_t^{i,y}, L_t^{i,y}\right)}{\partial L_t^{i,y}},$$

where δ is the capital depreciation rate and τ_t^i is the tax on capital and, hence, emissions. We multiply with π to get from x goods to composite goods. In case of y, we also multiply with the relative price between x and y, p.

3.3 Emissions

In the preceding sections, we have looked at the economic side of the model, only briefly mentioning the climate in the utility function section. Now, we introduce the The flow of emissions, e, at time t in country i is proportional to the capital stock.

$$e_t^i = \sum_l K_t^{i,l}.$$

Here index l runs over the sectors x and y. The stock of emissions, E, at time t is equal to the previous emission stock net of depreciation plus new emissions net of abatement. It is possible to abate a fraction, Ψ, of current emissions.

$$E_{t+1} = (1-\varepsilon)\cdot E_t + \sum_i e_t^i(1-\Psi)$$

Note that the emission stock is a public good shared by both countries. Therefore, next period's emission stock is given as the sum of both countries' current net emissions plus the previous period's stock of emissions net of depreciation.

3.4 Government

The government taxes pollution with a tax on capital return. The tax revenue from the green tax is

$$M_t^i = \tau_t^i \cdot \left[\left(\pi_t \cdot \frac{\partial F^x\left(K_t^{i,x}, L_t^{i,x}\right)}{\partial K_t^{i,x}} - \delta\right)\cdot K^{i,x} + \left(\pi_t \cdot p_t \cdot \frac{\partial F^y\left(K_t^{i,y}, L_t^{i,y}\right)}{\partial K_t^{i,y}} - \delta\right)\cdot K^{i,y}\right]$$

The tax revenue is simply a function of the total capital stock in both sectors. The total government income is the revenue from both the income tax and the green tax

$$B_t^i = M_t^i + \tau_l \cdot w_t^i \cdot L_t^i.$$

The government runs a balanced budget and spends the tax revenue on either investments in public consumption or abatement of domestic emissions. A fraction, μ, is on abatement, A^i, whereas the remaining tax revenue is spent on employees in the public sector, L^g.

$$A_t^i = \mu \cdot B_t^i \tag{2}$$

$$w_t^i L_t^{i,g} = (1-\mu)\cdot B_t^i \tag{3}$$

The abatement costs correspond to an abatement fraction of current emissions, Ψ, according to the following (Nordhaus 2014)

$$A_t^i = \lambda \cdot \Psi^{\phi} \cdot e_t^i$$

The function is convex in the abatement fraction which reflects that the most cost-efficient technologies are implemented first, leaving the less efficient to be implemented last. This means that the marginal abatement costs are increasing in the abatement fraction. The costs are also proportional to the level of the flow of emissions: All else equal, it is more expensive to abate x percent of a large flow than x percent of a small flow. Countries each have access to the same abatement technologies.

Individuals get utility from a publicly produced good. The public good is produced according to the following technology $G_t^i = \sqrt{L_t^{g,i}}$ and shared equally among individuals. This means that individuals get utility from e.g. the number of healthcare workers per citizen and not the absolute number of healthcare workers.

$$g_t^i = \frac{\sqrt{L_t^{g,i}}}{2N_t^i}$$

3.5 Equilibrium conditions

Market clearing in the goods markets implies that for each country i

$$\sum_i x_t^{s,i} = \sum_i \left(N_t^i \left(x_{y,t}^i + x_t^* \cdot \frac{s_t^i}{\pi_t} \right) + N_{t-1} \cdot x_{o,t}^i + x_t^* \cdot \frac{A_t^i}{\pi_t} \right) \tag{4}$$

$$\sum_i y_t^{s,i} = \sum_i \left(N_t^i \left(y_{y,t}^i + y_t^* \cdot \frac{s_t^i}{\pi_t} \right) + N_{t-1} \cdot y_{o,t}^i + y_t^* \frac{A_t^i}{\pi_t} \right), \tag{5}$$

where the left-hand side corresponds to total supply and the right-hand side is total demand.

If we rewrite all consumption terms such that they are measured in terms of composite goods, we get: $x_{y,t}^i = x_t^* \cdot c_{y,t}^i$, $y_{y,t}^i = x_t^* \cdot c_{y,t}^i$, etc. Using such manipulations in (4) and (5), and dividing the two yields a standard condition for clearing of the goods markets, namely that relative aggregate supply equals relative aggregate demand:

$$\frac{\sum_i x_t^{s,i}}{\sum_i y_t^{s,i}} = \frac{x_t^*}{y_t^*}. \tag{6}$$

Equilibrium in the capital market, is when next period's (global) capital stock is given as this period's total savings, i.e. when the demand for capital equals the supply of capital.

$$K_{t+1}^{w} = S_t^w \equiv \sum_i N_t^i s_t^i$$

Capital is shared between the four sectors (two in each country)

$$K_{t+1}^{w} = \sum_{i,l} K_t^{i,l}$$

3.6 The policymaker choosing the climate tax and abatement expenditures

We investigate the scenario in which countries choose their climate policy without coordinating with or caring about the interests of their trading partner. The policymaker in country i chooses her climate tax and abatement expenditures unilaterally to maximise steady-state utility of domestic individuals. Here with the tax as example, the policymaker faces the problem

$$\max_{\tau^i} \quad U_{ss}^i = \frac{\left(c_{y,ss}^i\right)^{1-\theta_c} - 1}{1-\theta_c} + \omega_g \cdot \frac{\left(g_{ss}^i\right)^{1-\theta_g} - 1}{1-\theta_g} - \omega_E \cdot E_{ss}^{\gamma} + \beta \left[\frac{\left(c_{o,ss}^i\right)^{1-\theta_c} - 1}{1-\theta_c} + \omega_g \cdot \frac{\left(g_{ss}^i\right)^{1-\theta_g} - 1}{1-\theta_g} - \omega_E \cdot E_{ss}^{\gamma} \right],$$

subject to optimal behaviour by individuals as outlined in Section 3.1, the government budget in (3), and taking the foreign climate tax as given. Contrary to the individuals, the policymaker is not atomistic, meaning that she internalises both budgetary effects and changes in factor prices stemming from her policy choice. The optimal tax satisfies the first-order condition $\frac{\partial U_{ss}^i}{\partial \tau^i} = 0$ and the second-order condition $\frac{\partial^2 U_{ss}^i}{\partial (\tau^i)^2} < 0$.

Because of interdependence between the two countries, the optimal climate tax in country i, $(\tau^i)^*$, is a function of the climate tax chosen in country j

$$\left(\tau^i\right)^* = h^i\left(\tau^j\right), \; i = H, F, \; j \neq i.$$

Here, $h^i\left(\tau^j\right)$ can be interpreted as country i's best response function as it gives the optimal policy response to any climate policy chosen by country j. The Nash-equilibrium is a combination of climate taxes $\left(\left(\tau^H\right)^*, \left(\tau^F\right)^*\right)$, where the countries mutually best respond. Or stated differently, it is a situation in which no country has an incentive to unilaterally change their climate tax:

$$\left(\tau^i\right)^* = h^i\left(\left(\tau^j\right)^*\right), \; \forall i = H, F, \; j \neq i \tag{7}$$

If we exchange the τ's with μ's, we have the policymaker's problem when she chooses abatement instead of taxes. Finally, we can include both τ's and μ's and get the two-dimensional problem where both taxes and abatement are endogenous. The behaviour of the policymaker, together with the behaviour of the individuals and the firms constitute the entire model. The agents act under the equilibrium conditions for market clearing, the government budget and the mechanical development of the climate as presented in the preceding sections. But before we can simulate the collective behaviour, we need a fully calibrated model.

4 Calibration

In this section, we present calibration of the parameters in a symmetrical world.

4.1 Economic parameters

We choose the parameter of relative risk aversion, θ_c, to 0.8 which corresponds to an elasticity of intertemporal substitution of 1.25. We use the same elasticity of intertemporal substitution for government consumption; i.e. $\theta_g = 0.8$. The share of time spent working for old individuals, R, is 0.5. With a generational span of 30 years, this corresponds to 45 years of work and 15 years of pension for our representative agent. One could imagine that the individual enters the model and starts working at the age of 20, retires at the age of 65, and dies at the age of 80.

The convexity parameter of the utility function, γ, is 2 which is in line with Weitzman (2010). With this choice, we ensure that damages are strictly convex, implying that the marginal damages are strictly increasing.

Recently, there has been substantial debate about the discount factor (Goulder and Williams III 2012). We choose $\beta = 0.7$ corresponding to a discount rate of approximately 1% per year with a generational span of 30 years. The depreciation rate for physical capital, δ, is 1 corresponding to full depreciation of capital over a generation.

We set the capital shares in the production of x and y to $\alpha_x = 0.33$ and $\alpha_y = 0.54$ corresponding to the estimates by Valentinyi and Herrendorf (2008) for the capital income shares in the US non-agricultural sectors and agricultural sector, respectively. The agricultural sector is a good proxy for the polluting sector since it accounts for around one fourth of global greenhouse gas emissions (IPCC 2014) and is almost unaffected by current green innovation. We also need to make a split between services and goods. Services constitute 65% of GDP (Bank 2016). We assume that government spending is constituted solely by services. This leaves consumption to consist of 43% services and 57% goods which in our benchmark year are the CES budget shares.

4.2 Climate parameters

The yearly decay rate for the emission stock is 0.00384 which corresponds to a rate of 0.109 over the span of a generation of 30 years which is what is proposed in Karp and Rezai (2017). We calibrate the abatement function with an abatement elasticity, ϕ of 2.5 (DICE-07). We follow Nordhaus (2014) such that it costs 5.4% of GDP to abate the current yearly flow of emissions which gives a λ of 0.566 [3].

4.3 Calibration of the utility-function weights

To calibrate the utility weights, ω_g and ω_E, we introduce two calibration constraints. The first constraint ensures that public spending constitutes 19% of GDP in steady state. General government final consumption expenditure consists of 16.9% of world GDP in 2018 according to Bank (2015). This covers all government spending except for transfers and pensions which we exclude from our calibration. In total, world government spending constitutes 27.49 % of World GDP according to Ortiz-Ospina (2016). Subtracting transfers and pensions, government spending ends up constitutes 19% according to the data above.[4] And consequently, private consumption and investment account for the remaining 81% of world GDP.

$$\frac{G^i_{ss}}{GDP^i_{ss}} = 0.19$$

The second constraint tells that a 2% decrease in steady state consumption should correspond to a 2 degree increase in temperature (4.8% increase in the stock of emissions) in utility terms. IPCC (2014) estimates that a 2 degree increase in pre-industrial temperature corresponds to an atmospheric concentration of CO_2 equivalents of 450 parts per million (ppm). Currently,

[3] $\lambda = \frac{0.054 \cdot y^H_{ss}}{e^H_{ss}} = \frac{0.054 \cdot y_{ss}}{K^H_x + K^H_y}$ because the world is symmetrical

[4] Transfers and pensions constitute 10.5% of world GDP. Subtracting these from GDP, government spending constitutes 16.9% of the remaining 89.5% yielding a total fraction of 19%.

we are at 430 ppm and thus the stock of GHGs can increase with 4.8% before we reach an increase of 2°C in temperature. We follow Weitzman (2010) and calibrate our model such that a 2°C increase in temperature corresponds to a 2% decrease in consumption in terms of lost utility.

$$U_{ss}^{i}\left(0.98 \cdot c, g, E\right) = U_{ss}^{i}\left(c, g, 1.048 \cdot E\right)$$

When imposing the two constraints and freeing the parameters ω_g and ω_e, we calibrate $\omega_g = 0.199$ and $\omega_e = 0.0000649$. Now, we have a fully calibrated model, with parameters as stated in Table 1. These choices constitute our benchmark specification.

Table 1: Baseline parameter specification

R : Fraction of time spent working when old	0.5
θ_c : Coefficient of relative risk aversion on consumption	0.8
θ_g : Coefficient of relative risk aversion on government consumption	0.8
ε : Carbon decay rate	0.109
α_x : Capital income share in sector x	0.33
α_y : Capital income share in sector y	0.54
φ_x : CES share - consumer preference for x	0.57
φ_y : CES share - consumer preference for y	0.43
ϵ : Substitution elasticity - between x and y	1
σ_x : Substitution elasticity - between K and L for x	1
σ_y : Substitution elasticity - between K and L for y	1
δ : Generational depreciation rate	1
β : Generational discount factor for utility	0.7
ρ : Returns to scale parameter	0.8
γ : Convexity parameter on emissions disutility	2
λ : Abatement weight	0.566
ϕ : Convexity parameter on abatement	2.5
τ_l : The tax on labour income	0.2
ω_g : The weight on government consumption in the utility function	0.199
ω_e : The weight on the climate in the utility function	$6.49 \cdot 10^{-5}$
N_t^i : The generation size	$1000 \ \forall \ i, t$

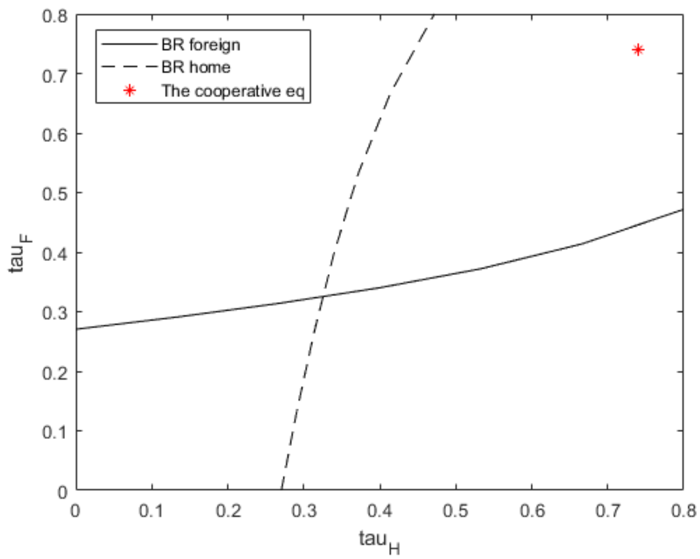
5 Results

We simulate best response functions for both countries and find the intersection point where the countries respond optimally to each other (The Nash equilibrium). In this point we want to determine what happens if one country changes its tax rate/abatement expenditures. Does the other country change its tax rate/policy mix in the same direction (indicating strategic complementarity) or in the other direction (indicating strategic substitutability)? Asking this is the same as asking for the sign of $\frac{\partial \tau}{\partial \tau^f}$ and $\frac{\partial \mu}{\partial \mu^f}$. We investigate this in a symmetrical world. In the first two sections, we look at one policy variable. I.e. either we keep the tax rate or the policy mix constant and let the other be determined endogenously. These simple one-policy-variable cases are informative about the different mechanisms at play. Having understood the different mechanisms, we move on to the case where both the tax rate and the policy mix are endogenous.

5.1 Endogenous climate tax

In our main specification, the government spends all its revenue on general government consumption. In the Nash equilibrium, the climate tax rate is 32.5% and the best response functions are upward-sloping, indicating that the climate taxes are strategic complements. See Figure 1. Here, tax competition and other channels leading to strategic complementarity dominates the incentive to free ride. The incentive to free ride stems from the fact that when one country improves the state of the climate, the other country's marginal gains from improving the climate decreases. But tax competition implies that it is less costly in terms of forgone production to increase taxes, the higher the other country's tax is; The country can increase their tax without fear of leakage. Furthermore, the Nash equilibrium is stable which can be seen from the slopes of the best response functions. If one country chooses a tax rate away from the Nash equilibrium, the process of each country responding to the other, will converge towards the Nash equilibrium. The asterisk represents the cooperative tax rate which, as predicted in the theoretical section, is higher than the non-cooperative tax.

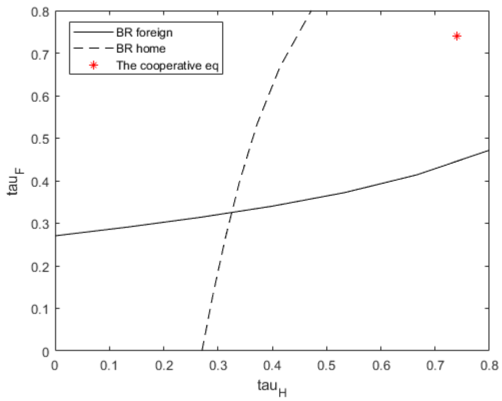
Figure 1: Example of best response functions of home and foreign country. The slopes are positive implying strategic complementarity.



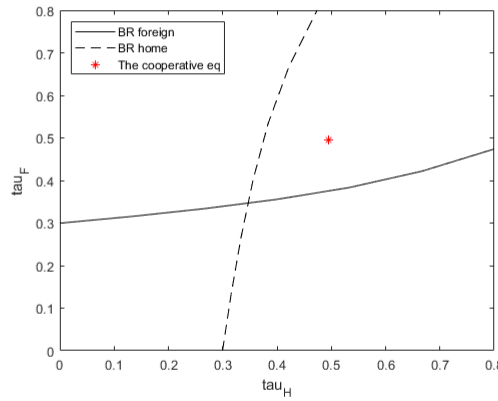
5.2 Different levels of exogenous abatement

When introducing different levels of abatement spending, the results gradually change. Abatement of greenhouse gas emissions is a world-wide public good - i.e. both countries equally benefit from one country's abatement. The higher the abatement fraction, the larger is the incentive to free ride because higher abatement levels leads to smaller marginal utility of abatement. In this section, we simulate best response functions for different levels of abatement. Figure 5 shows best response functions for when the two governments spend 0, 10, 30, and 50 percent of its revenues on abatement. In line with stronger free riding incentives, the best response functions gradually become flatter, and in the two last cases the best response functions are actually downward-sloping in the Nash equilibrium, meaning that the taxes are strategic substitutes. The graphs also show that the equilibrium taxes decrease. This means that the free-riding motives not only change the strategic interactions, but also affect how strong a climate tax rate the countries can uphold. The asterisk in each picture represents the cooperative tax rates. As we would expect based on the simple, theoretical model, the cooperative tax rates are all above the non-cooperative ones, indicating that countries unilaterally choose too low tax rates. This corresponds to the positive externalities associated with the climate tax, which countries do not take into account when they act non-cooperatively. The results are robust to changes in the retirement age. For robustness analysis, see Appendix C.

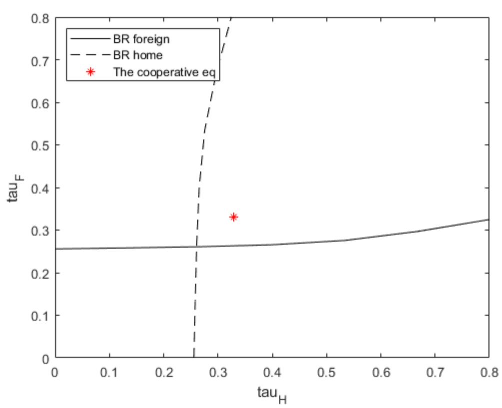
Figure 2: Best response functions for different levels of abatement



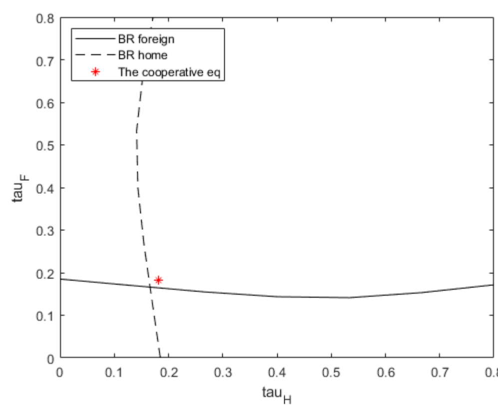
(a) Government spends 0% of tax revenue on abatement



(b) Government spends 10% of tax revenue on abatement



(c) Government spends 30% of tax revenue on abatement

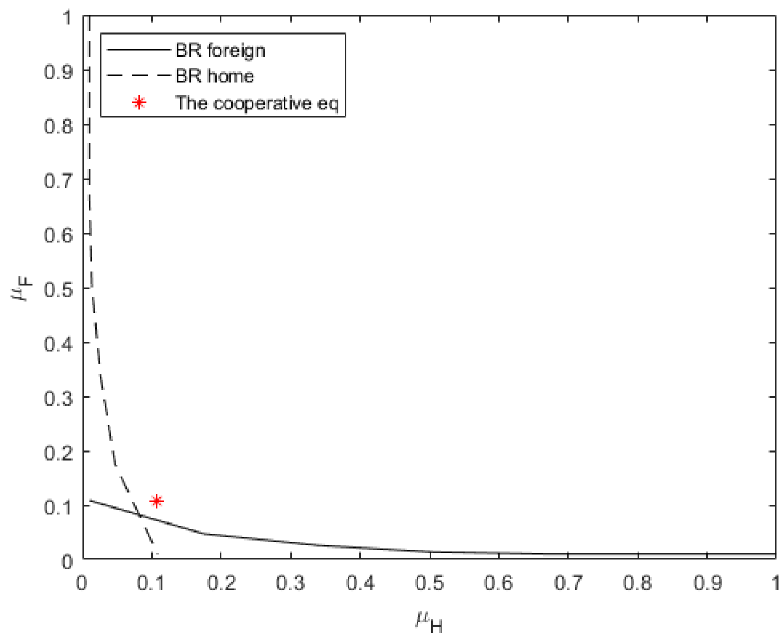


(d) Government spends 50% of tax revenue on abatement

5.3 Endogenous Abatement

Next, we keep the tax rates fixed and vary the abatement expenditures. For given tax rates, we want to understand the endogenous choices of the abatement levels chosen by the countries' policymakers. Figure 3 depicts best response functions when countries choose policy mixes for given tax rates, $\tau^H = \tau^F = 0.325$ which correspond to the baseline equilibrium tax rates. We observe that the best response functions are everywhere downward-sloping, and thus also

Figure 3: Example of best response functions in policy mix. The slopes are negative implying strategic substitutability.



in the Nash equilibrium, indicating strategic substitutability in the policy mix. This implies that if a country increases its share spent on abatement, it prompts its trade partner to lower theirs. Hence, the countries face a free-riding problem when they decide on their policy mix. Intuitively, this makes sense as the state of the climate is a public good and as changing the policy mix does not make tax competition less fierce, which previously was what allowed climate taxes to be strategic complements. Also, this result is in line with our previous findings in the theoretical part. Here, we saw that in the case of fixed taxes and endogenous policy mixes, only the free-riding motive was present. When the other country increases abatement, the home country's marginal utility of abatement decreases and thus the actions become strategic substitutes. As expected, the cooperative choice of the abatement share is higher than the non-cooperative solution because of the positive externalities associated with abatement.

5.4 The general two policy-variables case

In this section, we present results in the case where both the tax rates and the policy mixes are endogenous. Because of the dimensionality, we cannot present our results graphically. Instead, we take advantage of the *Banach fixed point theorem* to identify the non-cooperative Nash equilibrium.

Theorem 1 *Banach's fixed point theorem.*

Let (M, d) be a Metric Space, then a function $f : M \to M$ is said to be a contraction mapping if there exists a constant $q \in [0, 1)$ such that $\forall\ x, y \in M$: $d(f(x), f(y)) \leq q \cdot d(x, y)$.

If (M, d) is complete, then every contraction mapping has a unique fixed point.

It is possible to find the fixed point by numerical fixed point iteration, using $x^* = f(f(f(...f(x))))$. The best response function is a mapping from the closed unit interval onto itself: $f : [0, 1] \times [0, 1] \to [0, 1] \times [0, 1]$ which is obviously a non-empty, complete metric space when equipped with the Euclidean metric. So, if we assume it to be a contraction mapping as well, the theorem applies. Note, we do not rigorously prove the best response function to be a contraction mapping, but merely assume it to be so. *** Vær helt sikker her*** We find the Nash equilibrium by starting at an arbitrary point $x_0 \in [0, 1]$ and let the sequence $\{x_n\}$ defined by $x_n = f(x_{n-1})\,,\ n \geq 1$ converge.

Using this approach, we get the following non-cooperative $\left(\tau^{NC} = 0.3552,\ \mu^{NC} = 0.0716\right)$. In comparison, the cooperative equilibrium is $\left(\tau^{C} = 0.5316,\ \mu^{C} = 0.0857\right)$. Again, the difference owes to the fact that the externalities from the climate tax are positive, whereas shifting towards more public consumption at the expense of abatement is associated with negative externalities. Regarding, strategic substitutability/complementarity of policy tools, Table 2 shows how domestic policy variables, τ and μ, react in the Nash equilibrium when foreign policy variables, τ^f and μ^f, change. For instance, element $(1, 2)$ in Table 2 says that $\frac{\partial \mu}{\partial \tau^f} < 0$

	τ	μ
τ^f	+	-
μ^f	+	-

Table 2: How changes in foreign policy variables affect domestic variables in equilibrium

It is immediately evident that the one-dimensional results from above spill over 1-to-1 to the two-dimensional case in the sense that $\frac{\partial \tau}{\partial \tau^f} > 0$ and $\frac{\partial \mu}{\partial \mu^f} < 0$.

Regarding $\frac{\partial \mu}{\partial \tau^f} < 0$, this works in the opposite direction of $\frac{\partial \tau}{\partial \tau^f} > 0$ by lowering the share of the - now higher - tax revenue allocated to climate abatement. Said differently, the foreign increase in the climate tax increases the optimal domestic climate tax but lowers the share of the tax revenue spent on abatement.

In a similar fashion, an increase in the foreign budget share spent on abatement results in two counteracting effects on domestic abatement. On one hand, it increases the domestic tax rate. On the other hand, it lowers the domestic budget share allocated to abatement by inducing a free-riding incentive as shown analytically in Section 2.3 .

Summing up, more aggressive climate policies abroad through either τ^f or μ^f are met by domestic tax increases but also lower abatement shares. This exactly serves to prove our point; the issue of interaction climate policy is far more complicated than what is often portrayed in the existing literature and the public debate, and it could easily be the case that climate actions are not mutually negating but rather mutually reinforcing.

6 Conclusion

If everybody waits for somebody else to take action, nothing happens. A waiting game in the climate issue might arise for several reasons. First, decision makers may believe that it doesn't matter what one country does which leads to diffusion of responsibility. Second, they may want to wait for more information to be better equipped for the task. Third, they may believe that other countries will counteract their policy - so why bother? In this paper, we have look at the strategic nature of climate change mitigation policies. We consider both the size of the tax and the distribution of the revenue on either climate change abatement or general public spending. We find evidence that the free-riding effect does indeed play a role in the policy-maker's decision making. But it is not the only mechanism at play. When one country raise their climate tax, its trading partners face a smaller leakage externality if they want to raise their tax as well. Consequently, tax-competition effects and the free-riding argument may very well work in opposite directions, leaving no definitive answer on whether climate taxes are mutually reinforcing or, as is often presupposed in the existing literature, mutually negating.

Of course, we have several limitations to our setup. We only consider the steady-state equilibrium, and hence, do not account for the adjustment path. When it comes to climate change, the dynamics actually do matter because of the convex nature of damages and the relatively severe current state of the climate. Also, even though the debate about tipping points is controversial, it adds to the importance of time in climate models. Nevertheless, it lies beyond the scope of this paper to analyse the dynamics, but nevertheless, we have shown that the counteracting actions of the rest of the world in response to a climate tax might be less severe than one might think.

In the coming years, all countries will have to take a stance on the question of climate change mitigation. Presumably, they won't all cooperate and will be faced with the question of free-riding and strategic concerns. Of course, there are ways to accommodate free-riding problems if you fear for leakage. E.g. trade-policies like border tariffs and subsidies to leakage threatened industries. These policies are, however, not without political as well as economic side effects, and consequently, coordination problems are notoriously difficult. Our analysis provides insight into the consequences of non-cooperative climate policy.

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A Derivation of π

We drop the timing and country indexes, as it could be any country and happens within a time period. Plug in for constraint to get an unconstrained problem in one variable

$$\max_x \left(\varphi^{\frac{1}{\epsilon}} x^{\frac{\epsilon-1}{\epsilon}} + (1-\varphi)^{\frac{1}{\epsilon}} \left(\frac{1-x}{p}\right)^{\frac{\epsilon-1}{\epsilon}}\right)^{\frac{\epsilon}{\epsilon-1}}$$

The first order condition can be reduced to

$$\left(\varphi^{\frac{1}{\epsilon}} x^{\frac{\epsilon-1}{\epsilon}} + (1-\varphi)^{\frac{1}{\epsilon}} \left(\frac{1-x}{p}\right)^{\frac{\epsilon-1}{\epsilon}}\right)^{\frac{1}{\epsilon-1}} \left(\varphi^{\frac{1}{\epsilon}} x^{\frac{-1}{\epsilon}} - \frac{(1-\varphi)^{\frac{1}{\epsilon}}}{p} \left(\frac{1-x}{p}\right)^{\frac{-1}{\epsilon}}\right) = 0$$

For this to be zero, we must have that the second parenthesis is zero as the first one is definitely positive (provided that $x > 0$). Solving for the optimal choice of x, denoted with an asterisk, we get

$$\begin{aligned}
\varphi^{\frac{1}{\epsilon}} x^{\frac{-1}{\epsilon}} - \frac{(1-\varphi)^{\frac{1}{\epsilon}}}{p} \left(\frac{1-x}{p}\right)^{\frac{-1}{\epsilon}} &= 0 \\
\varphi^{\frac{1}{\epsilon}} x^{\frac{-1}{\epsilon}} &= \frac{(1-\varphi)^{\frac{1}{\epsilon}}}{p} \left(\frac{1-x}{p}\right)^{\frac{-1}{\epsilon}} \\
\varphi^{-1} x &= p^{\epsilon} (1-\varphi)^{-1} \left(\frac{1-x}{p}\right) \\
x &= p^{\epsilon-1} \left(\frac{\varphi}{1-\varphi}\right) (1-x) \\
x \left(1 + p^{\epsilon-1} \left(\frac{\varphi}{1-\varphi}\right)\right) &= p^{\epsilon-1} \left(\frac{\varphi}{1-\varphi}\right) \\
x^* = \frac{p^{\epsilon-1}\left(\frac{\varphi}{1-\varphi}\right)}{\left(1 + p^{\epsilon-1}\left(\frac{\varphi}{1-\varphi}\right)\right)} = \frac{1}{1 + \frac{1}{p^{\epsilon-1}\left(\frac{\varphi}{1-\varphi}\right)}} &= \frac{1}{1 + p^{1-\epsilon}\left(\frac{1-\varphi}{\varphi}\right)}
\end{aligned}$$

This implies that the optimal choice of y is

$$y^* = \frac{1-x}{p} = \frac{1 - \frac{1}{1+p^{1-\epsilon}\left(\frac{1-\varphi}{\varphi}\right)}}{p} = \frac{\frac{p^{1-\epsilon}\left(\frac{1-\varphi}{\varphi}\right)}{1+p^{1-\epsilon}\left(\frac{1-\varphi}{\varphi}\right)}}{p} = \frac{\frac{1}{1+\frac{1}{p^{1-\epsilon}\left(\frac{1-\varphi}{\varphi}\right)}}}{p} = \frac{\frac{1}{1+p^{\epsilon-1}\frac{\varphi}{1-\varphi}}}{p} = \frac{1}{p + p^{\epsilon}\frac{\varphi}{1-\varphi}}$$

The number of composite goods per x goods, which we denote π, is

$$\pi = c\left(x^*, y^*\right).$$

B Appendix theory

B.1 The signs of $\Omega_{\mu\tau^f}$ and $\Omega_{\tau\mu^f}$

We also want to know the effect of the foreign country changing its tax rate on the home country's choice of policy mix. That is, we want to find the sign of $\frac{d\mu}{d\tau^f}$. Again, we have that $sign\left(\frac{d\mu}{d\tau^f}\right) = \text{sign}\Big(\Omega_{\mu\tau^f}\Big)$ assuming that the other policy variables are constant. We find that

$$\Omega_{\mu\tau^f} = \Big(\mu v''_{gg}(\cdot) - (1-\mu)\, h''_{AA}(\cdot)\Big)\left[\tau f_{\tau^f}\right][\tau f] - h''_{AA}(\cdot)\left(1-\mu^f\right)\left[f^f + \tau^f f^f_{\tau^f}\right][\tau f]$$

The sign of the derivative is ambiguous because of several effects working at the same time. The last term is unambiguously positive, capturing the effect the other country's increased investments in the climate, which lowers the incentives of the home country to do the same. Instead they increase their share spend on general public consumption (corresponding to μ going up). On top of this, there is also a tax-base effect where several things are happening. First, both g and A increase for a given τ and μ in the home country because production is moved from abroad to the home country. The curvature of $h(A)$ and $v(g)$ together with the size of μ determine whether the marginal gain changes most for abatement or public consumption. The smaller the μ and μ^f, the more likely it is that the expression is positive.

Lastly, we investigate the sign of $\frac{d\tau}{d\mu^f}$. Again, we have sign $\left(\frac{d\tau}{d\mu^f}\right) = \text{sign}\Big(\Omega_{\tau\mu^f}\Big)$ under the same assumptions as previous. Here

$$\Omega_{\tau\mu^f} = -\left(\tau^f \cdot f^f\right) h_{AA}(\cdot)\left[(1-\mu)\,(\tau f_\tau + f) + (1-\mu^f)\tau^f \cdot f^f_\tau\right] - \tau^f f^f_\tau h_A(\cdot) \lesseqgtr 0$$

Two effects are at play. The first term is positive and represents the effect that when Foreign increases the share spent on public consumption, it increases the marginal benefit of investing in abatement (by increasing the domestic tax) for Home. The second, negative term captures that for a higher μ^f, the tax base effect is to a higher degree allocated to foreign, public consumption rather than abatement. This indirectly implies that it is more costly for Home to increase the tax rate as Home does not benefit from public consumption in Foreign as opposed to abatement in Foreign.

B.2 Signs with two policy variables

We have the social welfare function,

$$\Omega\left(\tau,\mu,\tau^{f},\mu^{f}\right)$$

, with the first order conditions

$$\Omega_{\tau}\left(\tau,\mu,\tau^{f},\mu^{f}\right)=0$$
$$\Omega_{\mu}\left(\tau,\mu,\tau^{f},\mu^{f}\right)=0.$$

If we total differentiate the FOC's, we get

$$\frac{d\tau}{d\tau^{f}}=-\frac{\Omega_{\tau\mu}\frac{d\mu}{d\tau^{f}}+\Omega_{\tau\tau^{f}}}{\Omega_{\tau\tau}} \tag{8}$$

$$\frac{d\mu}{d\tau^{f}}=-\frac{\Omega_{\mu\tau}\frac{d\tau}{d\tau^{f}}+\Omega_{\mu\tau^{f}}}{\Omega_{\mu\mu}}. \tag{9}$$

Insert (5) into (4)

$$\frac{d\tau}{d\tau^{f}}=-\frac{\Omega_{\tau\mu}\left(-\frac{\Omega_{\mu\tau}\frac{d\tau}{d\tau^{f}}+\Omega_{\mu\tau^{f}}}{\Omega_{\mu\mu}}\right)+\Omega_{\tau\tau^{f}}}{\Omega_{\tau\tau}}=-\frac{\left(-\frac{\Omega_{\tau\mu}\Omega_{\mu\tau}\frac{d\tau}{d\tau^{f}}+\Omega_{\tau\mu}\Omega_{\mu\tau^{f}}}{\Omega_{\mu\mu}}\right)+\Omega_{\tau\tau^{f}}}{\Omega_{\tau\tau}}.$$

Rearranging, we get

$$\begin{aligned}\frac{d\tau}{d\tau^{f}}\left(1-\frac{\frac{\Omega_{\tau\mu}\Omega_{\mu\tau}}{\Omega_{\mu\mu}}}{\Omega_{\tau\tau}}\right)&=-\frac{\Omega_{\tau\tau^{f}}-\frac{\Omega_{\tau\mu}\Omega_{\mu\tau^{f}}}{\Omega_{\mu\mu}}}{\Omega_{\tau\tau}}\frac{d\tau}{d\tau^{f}}\left(\frac{\Omega_{\tau\tau}-\frac{\Omega_{\tau\mu}\Omega_{\mu\tau}}{\Omega_{\mu\mu}}}{\Omega_{\tau\tau}}\right)\\
&=-\frac{\Omega_{\tau\tau^{f}}-\frac{\Omega_{\tau\mu}\Omega_{\mu\tau^{f}}}{\Omega_{\mu\mu}}}{\Omega_{\tau\tau}}\frac{d\tau}{d\tau^{f}}\\
&=-\frac{\Omega_{\tau\tau^{f}}-\frac{\Omega_{\tau\mu}\Omega_{\mu\tau^{f}}}{\Omega_{\mu\mu}}}{\Omega_{\tau\tau}-\frac{\Omega_{\tau\mu}\Omega_{\mu\tau}}{\Omega_{\mu\mu}}}\\
&=-\frac{\Omega_{\tau\tau^{f}}\Omega_{\mu\mu}-\Omega_{\tau\mu}\Omega_{\mu\tau^{f}}}{\Omega_{\tau\tau}\Omega_{\mu\mu}-\left(\Omega_{\tau\mu}\right)^{2}}\\
&=\frac{\Omega_{\tau\mu}\Omega_{\mu\tau^{f}}-\Omega_{\tau\tau^{f}}\Omega_{\mu\mu}}{\Omega_{\tau\tau}\Omega_{\mu\mu}-\left(\Omega_{\tau\mu}\right)^{2}}\end{aligned}$$

Because of the second order condition, we have

$$\operatorname{sign}\left(\frac{d\tau}{d\tau^{f}}\right)=\operatorname{sign}\left(\Omega_{\tau\mu}\Omega_{\mu\tau^{f}}-\Omega_{\tau\tau^{f}}\Omega_{\mu\mu}\right).$$

C Results when R = 1

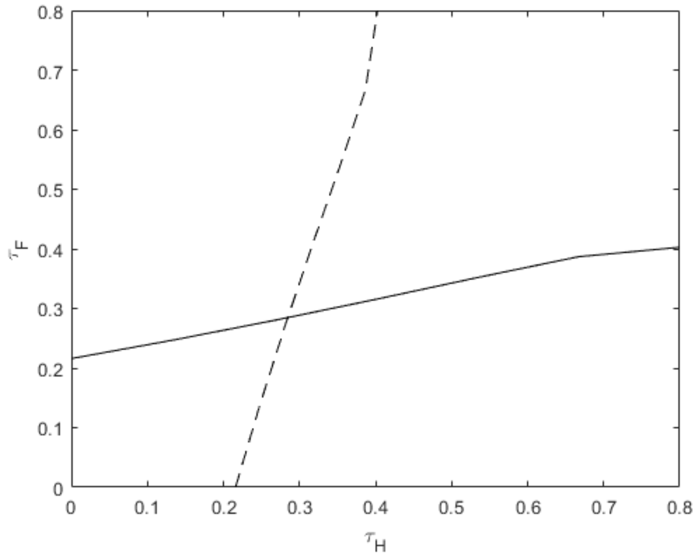
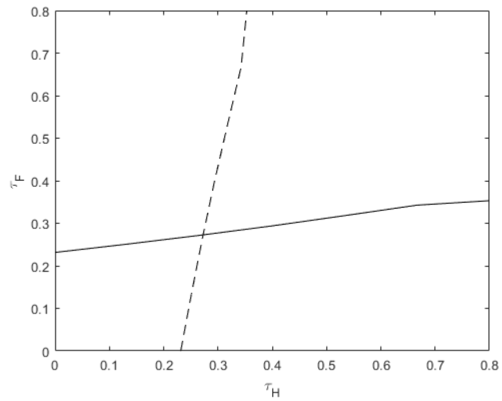
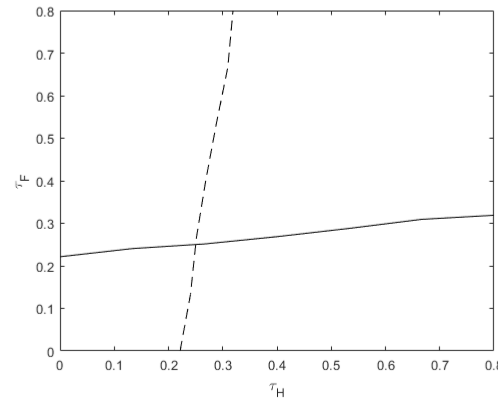


Figure 4: Result when $\mu = 1$ and $R = 1$

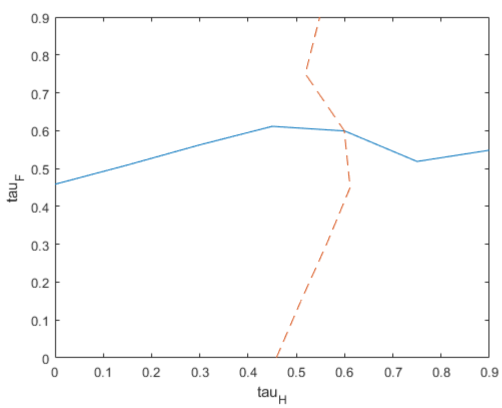
Figure 5: Best response functions for different levels of abatement



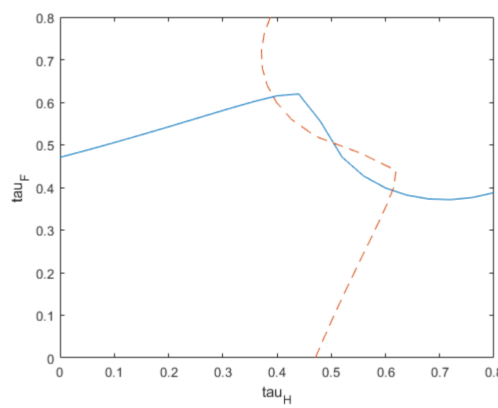
(a) Government spends 5% of tax revenue on abatement



(b) Government spends 10% of tax revenue on abatement



(c) Government spends 20% of tax revenue on abatement



(d) Government spends 25% of tax revenue on abatement

D R=0.5 and profit share=0.5

weights:

3.146231345069181 0.000022606916231

(calibration not entirely done but close to.)

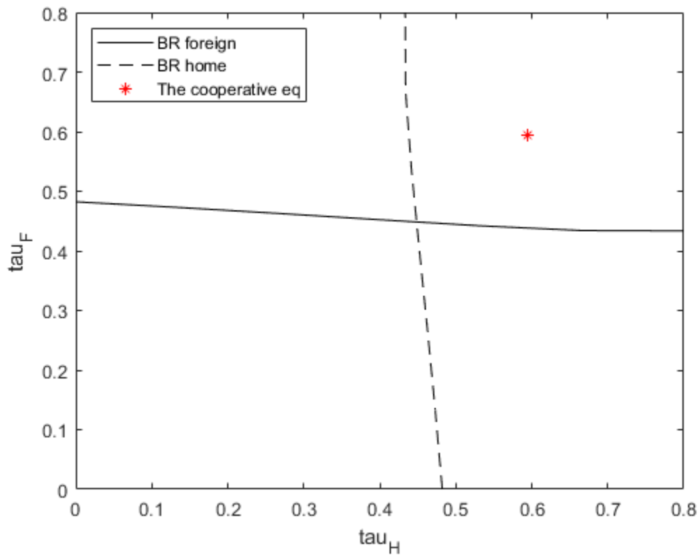


Figure 6