Jurisdiction heterogeneity and the stability of environmental tax coalitions

Erasmus University Rotterdam, the Netherlands

Abstract

We investigate how heterogeneity in capital endowment and sensitivity to environmental changes determine the composition and size of self-enforcing environmental tax coalitions. An existing tax competition model is adapted to allow for heterogeneous countries. Using a transfer scheme consistent with individual rationality, we find that coalitions are substantially larger and abatement is substantially higher when countries differ in their capital endowments and sensitivity to climate change. In case countries are asymmetric in their sensitivity to climate change, composition is dominated by a simple result: if benefits to free-riding rise as the number of signatories to the coalition increase, it's more beneficial to partner up to the other extreme of the spectrum directly, leaving countries with lower benefits to free-riding outside the coalition. Transfers are found to play a strong role in any scenario considered. Finally, we find that when poor countries are more sensitive to climate change than their rich counterparts, rich countries can exploit this by threatening to form coalitions under which poor countries are even worse off. This does however, result in the most relative abatement of all scenarios considered.

Keywords: Tax-competition, Self-enforcing environmental tax coalitions, Pollution abatement, Heterogeneous jurisdictions

Student: Winter van der Vlist
Student number: 348295

Supervisor: Hendrik Vrijburg

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1 Introduction

Economic utilization of shared resources like environmental quality suffers from what is known as the common pool problem. Collective well-being can be increased by managing the resources collectively through cooperation but each individual agent has an even bigger incentive to free-ride. To tackle this problem, the taxation literature still follows the seminal normative framework of Pigou [1920] for the simple case in which a single tax is applied in a closed-border setting. Extensive literature has already been written extending Pigou's first-best solution to second-best solutions for the more realistic case in which an environmental tax is part of a system of taxes (see for example King and Fullerton [2010]). This paper, however, concerns itself with the open-border setting. More specifically, it will zoom in on the strategic dilemma that arises between governments when determining the height of their environmental tax rates. Higher environmental tax rates scaring off industry is in part unavoidable but the degree to which industry is lost co-depends on environmental tax rates in other countries. This problem gets even more pronounced when the form of pollution is global, as with CO_2 emissions. When companies cross the border to carry on the same economic activities, no effective green result has been realized, a phenomenon referred to as carbon-leakage (see for example van der Meijden et al. [2015]). Typical is for example the following statement in a report of the Dutch government agency PBL in the context of environmental taxes (Vollebergh [2014]): "Many options for reforming the tax system demand international coordination due to tax competition". Benefits of cooperation are obvious, but in the absence of third parties that can punish free-rider behaviour, international cooperation takes place in the form of so-called international environmental agreements (IAEs) of which the Paris Agreement of 12 December, 2015 is the latest. As no country can be forced to sign an IEA, and countries can always withdraw from these agreements, IEAs must be attractive to sign as well as to carry out. IEAs having this feature can be regarded as being self-enforcing. The importance of this feature becomes apparent when reviewing the lack of success of earlier IEAs like the Kyoto protocol. The question is under what conditions IEAs are self-enforcing. Eichner and Pethig [2014b], assuming homogeneous jurisdictions and a pure global pollution (CO_2), show pessimistic results indicating that global cooperation is only self-enforcing when differences between cooperation and non-cooperation are small. The purpose of the current paper is to assess whether the more realistic, heterogeneous case holds more promise for cooperation. Concretely, we aim to answer the question:

"How does jurisdiction heterogeneity in capital endowments and sensitivity to environmental changes determine the size and composition of stable tax-coalitions and affect overall pollution abatement?"

The literature section discusses research on strategic environmental coalition formation using partial-equilibrium and general-equilibrium models. Literature on heterogeneity of countries in international cooperation has not fully rich yet and a range of modelling approaches, suited for different questions, have yielded mixed results. This makes it difficult to assess how differences between countries affect the stability of international environmental tax agreements (further IETA). We focus on the work of Eichner and Pethig [2014b].

Their general-equilibrium model has more economic structure than its partial equilibrium counterparts and reflects tax competition and carbon leakage well. By extending Eichner and Pethig [2014b]'s model to reflect heterogeneity in capital endowments and abatement costs, we retrieve, for a given coalition, the tax and welfare outcome of a strategic Nash game of tax rate setting by asymmetric countries. By defining how surplus welfare of cooperation is divided across coalition partners, the stability of coalition compositions is determined. We end with a grid search to map how mean-preserving heterogeneity of capital endowments and environmental damage affects global cooperation for different locations in the parameter space. To our knowledge there is no literature modelling heterogeneity of jurisdictions in a general-equilibrium framework except for a later article by the same authors (Eichner and Pethig [2014a]) where differences in sensitivity to climate change are considered between two groups of countries of equal size. We model continuous heterogeneity not only in sensitivity to climate change, but also in capital endowments and consider (negative) covariance between these asymmetries. Additionally, in contrast to Eichner and Pethig [2014a], we vary all parameters that are uniform across countries and capture a larger part of the parameter space in most dimensions. We use a visualization method utilizing opacity levels to render simulation results easily interpretable.

2 Literature review

2.1 Homogeneous jurisdictions

2.1.1 Partial equilibrium models

Modelling strategic games requires defining costs and benefits, putting assumptions on strategic behaviour and defining when coalitions are stable. Partial equilibrium models define benefits and costs directly; each country i's payoff P_i is defined by $P_i(x) = B(x_i) - D(x)$, where x is the vector of all emissions $x = (x_1, ..., x_n)$. In some papers climate coalitions are modelled as Nash players, the same as non-coalition countries. Some other papers model climate coalitions as Stackelberg leaders. All literature we considered use the stability concept d'Aspremont et al. [1983] introduced in oligopoly literature; a coalition is stable (self-enforcing) if none of the m jurisdictions within the agreement coalition (C) has an incentive to defect (internal stability) and none of the (n - m) outsider-jurisdictions (f for fringe) has an incentive to join the agreement (external stability). The general conclusion for models with Nash playing jurisdictions is that stable IEAs consist of 3 countries when marginal environmental damage is constant, and of 2 countries when marginal damage increases with emissions, in both cases irrespective of the number of countries modelled. Carraro and Siniscalco [1993] show that, in absence of commitment, transfers are unable to improve coalition size in a world with homogeneous jurisdictions. However, transfers can increase the number of signatories in presence of commitment schemes and can even lead to full cooperation. The common element of these commitment schemes is that a subset of jurisdictions are exogenously set to cooperative having as goal to enlarge the coalition, under the restriction that expansions do not adversely restrict any member of the coalition. This is equivalent to blocking free-rider behaviour for these jurisdictions. As McGinty

[2006] notes, the problem with this approach is that it is not a best-response and therefore violates individual rationality. Finus and Rübbelke [2013] consider local ancillary benefits of lowering global CO_2 emissions (e.g. a largely local benefit due to a corresponding drop in NO_x emissions). These are possibly quite considerable and may even exceed the primary benefits from slowing climate change(Pearce [2000]). One might expect that taking ancillary benefits into account partly alleviates free-riding incentives and hence raises the attractiveness of participation in international agreements to slow climate change. However, Finus and Rübbelke [2013] report a neutral to negative impact on the size of stable coalitions and the relative success of coalition formation measured in welfare terms. Countries with higher private benefits of emissions reduction, undertake more emission reduction, irrespective of international agreements. Research modelling the coalition as a Stackelberg leader reports different results. Depending on parameter values, a stable IEA can have any number of signatories between two and the grand coalition of all countries. But the gain in global welfare from the stable IEA relative to the non-cooperative outcome is inversely related to the number of signatories (see Barrett [1994]). The rationale for the difference in outcomes between Nash and Stackelberg models is that if a country leaves an IEA in a Nash game, the non-signatories expand their emissions and the remaining signatory countries partially accommodate this by reducing their emissions. In contrast, Stackelberg leaders will increase emissions in response to signatories leaving. Thus the incentive to leave an IEA is greater with Nash behaviour than with Stackelberg. Barrett [1994] does not restrict emissions to be non-negative and Diamantoudi and Sartzetakis [2006], restricting parameters to ensure non-negativity of emissions, find much smaller coalitions sizes. Rubio and Ulph [2006] argue however that this is an inappropriate manner to deal with non-negativity constraints. They use the Karush-Kuhn-Tucker conditions to impose restrictions directly on the choice of pollution x_i of each jurisdiction resulting in corner solutions for some parameter values. They find that, for the model considered, the size of the coalition is almost always the same for the constrained and the unconstrained problem and differs by 1 at most. The ultimate determinant of coalition size is the difference between payoff for signatories and non-signatories as the size of the coalition changes. A jurisdiction will join a coalition of size m if it's welfare is higher than what it would be if it remained a non-signatory. Whether an additional jurisdiction will join the new coalition of size $m+1$ depends on whether, under these new circumstances, this condition still holds. Rubio and Ulph [2006] show that, although the size of this difference is altered by restricting the emissions to be non-negative, the sign remains the same.

2.1.2 General-equilibrium models

Literature employing general-equilibrium models, model the interactions of the economies of the different jurisdictions. This makes this framework better suited for modelling a setting of tax competition. Taxes on capital for example can influence the terms of trade, providing a powerful incentive for countries to keep account of market reactions to the instruments employed. Ogawa and Wildasin [2009] model emission-tax-setting by individual countries as a Nash game in a world with a fixed supply of perfectly mobile capital. Environmental damage in country i is taken to be a linear function of capital used. Additionally, environmental damage in country i can spillover to country j with rate β_{ij} (0< β_{ij} <1). Country i's environmental tax rate t_i is therefore an instrument both to regulate environmental damage and to perform capital tax competition with. Ogawa & Wildasin use Nash equilibria to define tax-setting by individual jurisdictions: each jurisdiction optimizes its tax to maximize its own welfare, taking the tax rates of its complements as given. The level t_i chosen ultimately reflects the degree of tax competition and the jurisdictions disregard for spillovers. Remarkably, these effects cancel each other out when spillovers are taken to be symmetric ($\beta_{ij} = \beta_{kl}$). Ogawa & Wildasin conclude that it is not the first order existence of spillovers that call for the centralization of this type of policy, but rather the second order differences in spillovers ($\beta_{ij} \neq \beta_{kl}$). Eichner and Runkel [2012] show that Ogawa's & Wildasin's result depends strongly on the assumption of fixed capital supply. Modelling homogeneous countries over two periods, they describe an endogenous process of capital supply and find that the first order existence of spillovers already causes capital tax rates to be inefficiently low. Higher capital tax rates force capital away from investments where net-of-tax yield now falls below the old marginal cost of capital until a new equilibrium is reached with a lower interest rate and a lower global capital stock. As a result, higher capital tax rates do affect total capital supply and hence emissions. When country i raises its tax rate, countries $j \neq i$ experience an influx of capital, to which they adjust their tax rates. Pollution in countries $j \neq i$ increases but not enough to offset the decline in pollution in country i. In presence of spillovers ($\beta_{ij} \geq 0 \; \forall \; i,j$), countries $j \neq i$ benefit from reductions in country i's pollution. Country i, however, does not take this into account when setting its tax rate resulting in inefficient tax policy. An equilibrium in which states are assumed to set their tax policies independent from one another, can be regarded as a non-cooperative Nash equilibrium and we will follow **?** by referring to it as the 'Business as Usual' (BAU) scenario. Eichner & Pethiq use the model design of Eichner & Runkel to explore stable coalition when countries play Nash. They insert parameterized functions and assess stability of different coalition sizes for a large parameter space. They conclude that stable coalitions consists of m = 2 or m = 3 countries for the scenarios where taxes are strategic substitutes or strategic complements respectively. The number of countries in the parameter space ranges from n = 10 to n = 200. Hence stable coalitions are small both in absolute as in relative terms. A part of the parameter space considered also shows stability for the grand coalition, containing all countries, along with the earlier identified m = 3. It turns out that strategic complementarity is a necessary but insufficient condition for the grand coalition to be stable (roughly speaking tax rates should be strong complements). Eichner & Pethiq show that in order to assess the promise self-enforcing IETAs hold in reality, the strategic employment of taxes can serve as a straw in the wind. Conditions under which taxes are strategic substitutes/complements can be inferred within the context of a model as is done by examining the effect model parameters have on the sign of the reply functions as done above. The parameters in the model of Eichner & Pethig however, do not have a clear absolute interpretation. Vrijburg and de Mooij [2015] also explore the conditions under which taxes are strategic substitutes/complements, but do so using a parametrization that maps to quantities commonly used in economic literature. Doing so, they are able to illustrate the role the marginal rate of substitution between public and private goods and the marginal cost of public funds have. Additionally, they also consider the effect asymmetric capital endowments have on the likelihood of tax rates being strategic complements. As in Eichner & Pethiq, the solutions show a description of a higher dimensional space. No one country characteristic (dimension) can ensure strategic complementarity/substitutability. A more direct approach to assess these quantities is empirical observation. Past papers report mixed results. Devereux et al. [2008] and Overesch and Rincke [2011] find that on average tax rates show complementary behaviour. Chirinko and Wilson [2011] account for lags and common shocks by using the Peseran estimator (Pesaran [2006]) in a panel data set of states in the U.S.. Contrarily they find a negative slope for the tax reaction functions which implies strategic substitutability.

2.2 Heterogeneous jurisdictions

The assumption of homogeneity is an obvious departure from reality. Empirical research suggest for example that both benefits and costs of pollution abatement differ strongly between nations (see Ellerman et al. [1998]). Carraro and Siniscalco [1993] note that most existing IEAs deploy a system of transfers from rich countries to poor countries. It is unclear how heterogeneity of countries affects the emergence of cooperative structures. Analysis is considerably more complicated because stability is dependent on the absence of profitable deviations. Using brute force by checking all possible transitions between $\sum_m^n \binom{n}{m}$ different coalition structures is untenable even for a small number of countries n. Additionally, unlike the homogeneous case, transfers are not a priori useless which makes their design a new source of discussion. Almost all literature considered employs a form of transfers, the effects of which varies. Put more formally, for a country to join a coalition means to agree to maximize the coalitions aggregate welfare and to agree upon a so-called bargaining rule according to which potential welfare gains are distributed among its members (Burbidge et al. [1997]). This means that, given a coalition structure and a bargaining rule, Nash equilibrium tax rates and according welfare levels are determined. When states have perfect information about the outcome that would be attained for different coalition structures, each state will have in advance a preference ordering of coalition structures. Bernheim et al. [1987] give a strong definition for heterogeneous coalition stability. Their coalition-proof Nash equilibrium (CPNE) defines stability recursively; a coalition is stable if no subset of states, taking the strategies of its complement as fixed, can fashion a profitable deviation for each of its members that is itself immune to further deviations by subsets of the deviating coalition. Burbridge et al. describes how endogenous coalition formation could work in the form of so-called partnership plans to be proposed at the start of the game. Research in environmental coalition formation however, does not use endogenous models of coalition formation, but sticks to the concept of stability. Furthermore, in order to get results, considerable simplifications are made to the concept of stability. Barrett [2001] evaluates asymmetry in benefits of abatement in a partial equilibrium model. To obtain analytic results, he limits the scope of analysis to asymmetry between two groups. Barrett shows that countries with a relatively large benefit of cooperation have an incentive to buy cooperation of non-signatory countries. Under certain asymmetry conditions, equilibrium compensation will follow the scheme employed in the successful Montreal Protocol (protection of the ozon layer): the 'rich' countries pay the ‘poor’ just enough to cover their incremental cost of joining the coalition. This will not result in indifference for ’poor’ countries as the total gain of accession will result in a net benefit. Effectively, cooperation is bought. McGinty [2006] adapts the original partial-equilibrium model of Barrett [1997] to allow for mean-preserving jurisdiction heterogeneity in both benefit of abatement as well as marginal cost of abatement. McGinty proposes a bargaining rule under which coalition members get the welfare they would obtain if they would defect from that coalition. Any surplus is distributed according to the benefit-cost ratio of abatement. This is essentially an allocation rule that satisfies the rule found by Barret (2001) but is a bit more generous as it also divides the remaining coalition benefit according to the benefit-cost ratio. In both cases the condition for coalition stability can be expressed as: $\sum_j W_j^C > \sum_j W_j^{C_{\setminus j}}$, where $C_{\setminus j}$ denotes the coalition C excluding country j. After ensuring that every jurisdiction has enough to guarantee stability, Barret stops and McGinty continues to divide the surplus. McGinty [2006] finds that, in the absence of global cooperation, asymmetry increases abatement when high benefit nations are also low cost. Or put differently, negative co-variance between the heterogeneous parameters typically indicates that the non-cooperative level of abatement is higher than with symmetric countries. Also, the full cooperation level of abatement is unambiguously higher when nations differ. McGinty uses simulations to find that welfare gains from self-enforcing IEAs are substantially higher than for the symmetric case due to increased cooperation although still falling short of the grand coalition. In case high benefit nations also have low costs of abatement, the HiLo scenario, abatement is high even in absence of cooperation. In case high benefit nations are also high costs, the HiHi scenario, abatement levels are substantially increased through the use of cooperation, as low-cost abatement options in low-benefit countries are made use of. His results indicate that when gains to cooperation are largest, pollution abatement is substantially higher when jurisdictions differ in benefits and costs. Contrast this to the results of the homogeneous model by Eichner & Pethiq where cooperation was only stable for those parameter constellations where gains to cooperation were small. Fuentes-Albero and Rubio [2010] and the comment by Glanemann [2012] analytically consider dichotomous asymmetry in benefits of pollution and vulnerability to pollution damage in a partial-equilibrium model. He considers the two asymmetries separate from each other and finds that heterogeneity only increases cooperation in the presence of transfers schemes. The degree of pollution abatement with transfers increases strongly as differences in environmental damages between the two groups of countries get bigger. Pavlova and De Zeeuw [2013] analytically consider simultaneous dichotomous asymmetry in benefits of pollution and vulnerability to pollution damage in a partial-equilibrium model. They show that this flexibility allows for large stable coalitions even in absence of transfers. However, asymmetry between the two groups of countries must be big and the gains of cooperation small. They also find that allowing for transfers in a similar fashion to McGinty [2006] eases the asymmetry requirements for stability but not dramatically so. Transfers may increase gains of cooperation when asymmetry in pollution benefits are small and differences in vulnerability to environmental damage is large. These requirements are relaxed when the number of countries that are less vulnerable and have high marginal pollution benefits increases. Compared to the homogeneous case, Pavlova & De

Zeeuw find that total pollution abatement is lower in the case without transfers and possibly higher in the case with transfers. These result contrast sharply with those of McGinty. Biancardi and Villani [2014] also employ a partial-equilibrium model but consider rich countries and poor countries in a dynamic setting. They conclude that the asymmetry in valuation of emission abatement is unimportant: stable coalitions remain small and the grand coalition is stable only in the presence of transfers. Rich countries are always the net contributors to coalitions. In a later paper Eichner & Pethiq (Eichner and Pethig [2014a]) developing on their 2013 paper regarding international trade, review how the capacity of international trade to generate gains from cooperation varies with dichotomous heterogeneous benefits and costs of pollution abatement. Disregarding the transfers systems that were seminal in the papers of Barrett (2001) and McGinty (2007) they find that heterogeneity forms an obstacle to cooperation. They find that climate damage asymmetry discourages cooperation. The effects of fuel-demand asymmetry depend on fossil fuel abundance. If fuel is sufficiently scarce, low degrees of fuel demand asymmetry discourage cooperation whereas higher degrees of asymmetry stabilize the grand coalition. If fuel is very abundant, however, the grand coalition fails independent of the degree of fuel demand asymmetry. Table 1 summarizes the literature discussed subdividing the work in four classes to give a better idea of the contribution of the current paper. Apart from filling a gap in the typology marked in Table 1, the current paper differs from all heterogeneous literature discussed by not defining heterogeneity dichotomous but rather continuous, with which we hope to illustrate compositional features of stable tax coalitions.

Table 1: Literature overview and typology

	Partial equilibrium	General Equilibrium
Homogeneous	Carraro and Siniscalco (1993) Barrett (1994) Diamantoudi and Sartzetakis (2006) Rubio and Ulph(2006) Finus and Rubbelke (2013)	Eichner & Pethiq(2014b)
Heterogeneous	Barrett(2001) McGinty(2006) Pavlova and De Zeeuw (2013) Biancardi Vilani (2014)	Eichner & Pethiq(2014a) (no tax competition) Current paper

3 Model

3.1 Reply-functions

We expand on the endogenous mobile capital supply model of Eichner & Pethiq (2014b). Their general-equilibrium model has a strong tax competition framework. By linking a countries pollution to capital use, the model in our opinion reflects well the fear that industry will leave the country in response to unfavourable tax conditions that often shapes political agendas.[1] Higher taxes essentially affect the intertemporal consumption decision in favour of first-period consumption which is assumed to be favourable for the environment. We feel that this is justifiable as more immediate consumption will in reality be at least partly realized by consuming more leisure and less material consumption. Also, by taking capital-endowments as a source of heterogeneity, the model reflects the dichotomy of 'developed countries' and 'developing countries' that has characterized existing IEAs. In this section we discuss our model and point out where our model differs from that of Eichner & Pethiq. Although we allow for heterogeneity in all parameters in the derivation, we restrict our simulations later to heterogeneity in just two parameters. Consider a two-period economy with n $\geq$ 2 identical countries each inhabited by a representative household. At the beginning of the first period country i's resident is endowed with $\bar{k_i} > 0$ units of capital which she plans to use for living in both periods. Each country produces a consumption good in each period. In the first period capital can be transformed into a consumption good according to $x_i^1 = k_i^1$. Correspondingly, $s_i = \bar{k}$ - $k_i^1 = \bar{k}$ - x_i^1 is the consumers savings which will be supplied on the second-period world capital market. In each country i, a representative firm employs the k_i units of capital to produce the (second-period) consumption good according to the production function

$$x_{is}^2 = X_i(k_i), \qquad X_i' > 0, \qquad X_i'' < 0. \tag{1}$$

This production process generates emissions, e_i, in strict proportion to capital employed which we, in contrast to Eichner & Pethiq, allow to differ per country. This can be expressed as $e_i = \psi_i\ k_i$ with $\psi_i > 0$ and constant. Emissions are regulated in each country by means of an emission tax at rate t_i (effectively a tax on capital). The global interest rate is detated as r. After tax profit is $\pi_i = X_i(k_i)$ - $(1 + r + t_i\ \psi_i)k_i$. Maximizing this profit and taking the consumption good in the second period as numeraire yields:

$$X_i'(k_i) = 1 + r + t_i\psi_i \tag{2}$$

For capital supplied the consumer receives capital income (1+r)s_i in the second period as well as profit π_i earned by the domestic second-period firm. This leads to the following second period budget:

$$x_i^2 = (1 + r)s_i + \pi_i + t_i\psi_i k_i \tag{3}$$

Where $t_i\psi_i k_i$ are the lump sum tax transfers from the government to the household. As households are affected by global pollution $\sum_j e_j$, the utility function is given by:

[1]See Fullerton (2010) p. 464-467 for a discussion of this problemacy

$$U_i(x_i^1) + x_i^2 - D_i\left(\sum_j e_j\right), \qquad U_i' > 0, U_i'' < 0, \qquad D_i' > 0, D_i'' > 0. \tag{4}$$

Similar to the production function, a quadratic specification is taken for first period consumption and a linear specification for second period consumption. For our heterogeneous model this has the attractive property that, although absolute differences in utility exist, the marginal utility of capital will be constant across countries. This ensures that transfer schemes have no feedback mechanisms; monetary transfers in the second period are equivalent to a direct transfer of welfare. Maximizing the private part of the utility function w.r.t. savings subject to the budget constraint gives U_i'($\bar{k}$ - s_i) $= 1 +$ r. This equation expresses savings as a function of the interest rate. Capital and second-period consumption goods are traded on perfectly competitive world markets. The condition

$$\sum_j s_j = \sum_j k_j \tag{5}$$

clears the capital market. Walras's Law dictates that the world market for the second-period consumption good is also in equilibrium if and only if this condition holds. Explicit formulas are inserted for the utility, production and damage functions:

$$X_i(k_i^1) = \alpha_i k_i^1 - \frac{\beta_i}{2}(k_i^1)^2, \quad D_i\left(\sum_j e_j\right) = \frac{\delta_i}{2}\left(\sum_j \omega_{ji} e_j\right)^2, \quad U_i(x_i^1) = a_i x_i^1 - \frac{b_i}{2}(x_i^1)^2. \tag{6}$$

These functional forms differ from Eichner & Pethiq by allowing for heterogeneity in all parameters as well as the introduction of the parameter ω_{ji}. As capital tax competition and environmental tax incentives are intertwined in this model, the question arises to what extent coalition formation would have arisen purely for reasons of tax competition. We therefore, introduce the parameter ω_{ji} which reflects the locality of the environmental damages. ω_{ji} is the fraction of emissions by country j that cause damage in country i. For the global case this means that $\omega_{ji} = 1, \forall i, j$. For a pure local pollution, $\omega_{ji} = 1, i = j$ and $\omega_{ji} = 0, i \neq j$. This parameter can also be used to model asymmetries in the level of spillovers (for instance due to geographical conditions like rivers and wind currents), but this falls outside the scope of this paper. δ_i should be interpreted as the sensitivity of country i to climate change (for instance due geographical position) and not as a parameter for demand for a clean environment. Although the latter interpretation is equivalent at this stage, it conflicts with the later assumption that all households (utility functions) are the same. Moreover, interpreting it as such leads to an inconsistent framework when covariance between capital endowments and such climate sensitivity is considered. Any further wealth obtained by strategic success should affect δ_i. Such feedback mechanisms fall outside the scope of this paper. Maximization of utility and production functions w.r.t. respectively s_i and k_i:

$$s_i = \frac{1 - a_i + r}{b_i} + \bar{k}, \qquad k_i = \frac{\alpha_i - 1 - r - t_i\psi_i}{\beta_i}. \tag{7}$$

Substituting these results into the market clearing condition and solving for r:

$$r = \eta \sum_j \left(\frac{(\alpha_j - 1 - t_j\psi_j)b_j - (1 - a_j)\beta_j}{b_j\beta_j} - \bar{k_j} \right) \tag{8}$$

Where $\eta = \left(\sum_j \left(\frac{b_j+\beta_j}{b_j\beta_j}\right)\right)^{-1}$. Substituting r back in the equations of s_i and k_i yields expressions in terms of the model parameters and t_i. Accounting for x_i^1 = $\bar{k}$ - s_i and x_i^2 = X(k_i) + (1+r)(s_i - k_i) the countries welfare function can be expressed as.

$$W^i(t_i, ..., t_n) := U(\bar{k} - s_i) + X(k_i) + (1 + r)(s_i - k_i) - D(\sum_j e_j). \tag{9}$$

We, unlike Rubio and Ulph [2006] do not use Karush-Kuhn-Tucker conditions to satisfy logical constraints. Although their method is to be preferred, it considerably complicates analysis. We, like Eichner and Pethig [2014b], simply look for interior solutions and disregard outcomes that do not satisfy the criteria. Reply functions can be found by setting the first derivative w.r.t. taxes to zero.

Business as usual

In the BAU scenario every country uses its own tax rate t_i to optimize its own welfare, keeping the behaviour of the other jurisdictions as fixed. Setting the first derivative of the welfare function w.r.t. t_i equal to zero and letting the subscript of the function represent the variable w.r.t. which the derivative is taken gives

$$W^i_{t_i} = -U_{s_i}(\bar{k_i} - s_i)\frac{\partial s_i}{\partial t_i} + X_{k_i}(k_i)\frac{\partial k_i}{\partial t_i} + \frac{\partial(1 + r)(s_i - k_i)}{\partial t_i} - D_{\sum \omega_{ji} e_j}\left(\sum \omega_{ji}e_j\right)\frac{\partial \sum \omega_{ji}e_j}{\partial t_i} = 0. \tag{10}$$

Which can be rewritten as

$$W^i_{t_i} = t_i\psi_i\frac{\partial k_i}{\partial t_i} + (s_i - k_i)\frac{\partial r}{\partial t_i} - \kappa_{ii}\sum_j \omega_{ji}e_j = 0 \tag{11}$$

Where $\kappa_{ip} = \delta_p\left(\eta\sum_j\left(\frac{\omega_{jp}\psi_j\psi_i}{\beta_j\beta_i}\right) - \frac{\omega_{ip}\psi_i^2}{\beta_i}\right)$. These terms represent respectively; marginal benefits from tax revenue, marginal benefits/costs of interest (affected by tax) payed/received on the terms of trade and the marginal benefit of an improvement in environmental quality due to raising t_i. This equation can be expressed as a function of the taxes and parameters for each country i:

$$\left(\frac{\eta^2\psi_i(b_i + \beta_i) - \kappa_{ii}\eta b_i\beta_i^2\sum_j\frac{\omega_{ji}\psi_j}{\beta_j}}{b_i\beta_i^2}\right)\left(\sum_j\frac{t_j\psi_j}{\beta_j}\right) + \kappa_{ii}\left(\sum_j\frac{t_j\omega_{ji}\psi_j^2}{\beta_j}\right)$$
$$-\left(\frac{t_i\psi_i^2}{\beta_i}\right) - \left(\frac{\psi_i\eta\zeta + \kappa_{ii}\beta_i\sum_j\omega_{ji}\psi_j\chi_j}{\beta_i}\right) = 0.^2 \tag{12}$$

[2]Dropping the parameter subscripts, this condition reduces to the f.o.c. found by Eichner & Pethiq. The full derivation can be found in the appendix

Where

$$\chi_i = \frac{\alpha_i - 1}{\beta_i} - \frac{\eta}{\beta_i}\left(\sum_j \frac{(\alpha_j - 1)b_j - (1 - a_j)\beta_j}{b_j\beta_j} - \bar{k_j}\right) \tag{13}$$

$$\zeta_i = \frac{1 - a_i}{b_i} - \frac{\alpha_i - 1}{\beta_i} + \eta\left(\frac{b_i + \beta_i}{b_i\beta_i}\right)\left(\sum_j \frac{(\alpha_j - 1)b_j - (1 - a_j)\beta_j}{b_j\beta_j} - \bar{k_j}\right) + \bar{k_i}. \tag{14}$$

The sign of the reaction function w.r.t. taxes of other jurisdictions determines whether taxes are strategic complements or substitutes. Country i responds to tax changes by other jurisdictions because their actions affect the marginal benefits named above. This however is not true of the first benefit listed; the marginal benefit from tax revenue is unaffected by tax changes in other jurisdictions. Analysis of the reply function shows that country i will raise its tax rate t_i in response to a raise in tax rate t_k if $\kappa_{ii}\left(\frac{\omega_{ki}\psi_k^2}{\beta_k} - \eta\frac{\psi_k}{\beta_k}\left(\sum_j \frac{\omega_{ij}\psi_j}{\beta_j}\right)\right) + \eta\frac{\psi_k}{\beta_k}\eta\frac{\psi_i}{\beta_i}\frac{b_i+\beta_i}{b_i\beta_i}$ is positive. The first term describes how marginal environmental damage in country i changes in response to changes of its own tax rate t_i, as country k raises its tax rate t_k. When country k raises its capital tax, the capital stock's size and allocation across countries changes, which in turn changes the total environmental damage in country i. As the damage function is quadratic, country i's marginal damage of pollution has changed, and hence the environmental benefits of its own tax rate t_i. The second term captures the change in marginal benefit from higher taxes due to affecting the interest received (payed) on capital export (import). For example, a country i with small capital endowments will likely import capital, providing it with an incentive to tax capital for tax revenue purposes but also to negatively affect capital import and hence interest paid. Its tax rate also affects the interest rate which should be taken into account when optimizing its tax rate. However, when taxes of other jurisdictions change, the interest rate will respond differently to changes of its own tax rate t_i. To get a better idea of the net effect each parameter has on the strategic behaviour of jurisdictions, we look at the homogeneous counterpart of this condition as found by Eichner & Pethig. Strategic complementarity holds if $b(b+\beta) - n^2\beta\delta\psi^2$ is positive. Eichner & Pethig use simulations to show that the likelihood that the grand coalition is stable increases as $b(b+\beta) - n^2\beta\delta\psi^2$ increases. This means that b should be sufficiently large and β, n, δ and ψ must not be too large. Eichner & Pethig illustrate the effect of b by observing that $x_i^1 = (\alpha - 1 - r)/b$ is the amount of good X consumed in the first period. As b rises, increasing shares of production and consumption are shifted to the second period. Consequently, the two-period model of Eichner & Pethig approaches the one-period model of Ogawa and Wildasin (2009) in which the BAU allocation is efficient. This in turn means that welfare gained by moving from BAU to the social optimum diminishes with increasing parameter b (for large b). For the homogeneous case this means that the grand coalition is only stable for cases in which gains to cooperation are small.

Social optimum

The social optimum corresponds with full-cooperation and is therefore equivalent to the taxes that would be chosen by the grand coalition. Unlike Eichner & Pethiq we cannot make use of any symmetry assumption at this point. For most asymmetries in country parameters, tax rates will be the same but not for all. Consider how an all-knowing planner would set the vector of tax rates $\{t_1,...t_n\}$ if units of capital generate different levels of emissions across countries (asymmetric ψ_i's). Differentiating taxes to 'push' capital to countries with efficient technology will allow for higher welfare in this scenario. As there are no free-rider concerns, the tax rates in this scenario are set at their Pigouvian level; they are equal to the global marginal damage of pollution. Optimizing $\sum_j W^j$ over $\{t_1,... \ t_n\ \}$ we find $\forall\ i$

$$\left(\frac{\eta\psi_i - \eta\beta_i \sum_j \kappa_{ij}\left(\sum_p \frac{\omega_{jp}\psi_j}{\beta_j}\right)}{\beta_i}\right)\left(\sum_j \frac{t_j\psi_j}{\beta_j}\right) + \sum_j \kappa_{ij}\left(\sum_p \frac{t_j\omega_{jp}\psi_j^2}{\beta_j}\right)$$

$$-\left(\frac{t_i\psi_i^2}{\beta_i}\right) - \left(\sum_j \frac{\eta\psi_i\zeta_j + \beta_i\kappa_{ij}(\sum_p \omega_{pj}\psi_p\chi_p)}{\beta_i}\right) = 0. \tag{15}$$

Note also that the presence of an all knowing planner does not imply the need for transfers. Maximum welfare is assured without transfers as marginal utility of consumption is constant across jurisdictions. All countries continue to use capital in the first period to satisfy first period consumption, until its marginal benefit equals $\frac{1}{1+r}$; the marginal utility of second period consumption.

Climate coalitions

The previous scenarios are special cases of a coalition; for the situations in which the coalition structure is all-singletons, or the grand-coalition. We find the following best-reply function for coalition members by maximizing the summed welfare of all coalitions members. A coalition C's best reply function reads

$$\left(\frac{\eta^2\psi_i \sum_{p\in C}\left(\frac{b_p+\beta_p}{b_p\beta_p}\right) - \eta\beta_i \sum_{p\in C}\kappa_p\left(\sum_j \frac{\omega_{jp}\psi_j}{\beta_j}\right)}{\beta_i}\right)\left(\sum_j \frac{t_j\psi_j}{\beta_j}\right)$$

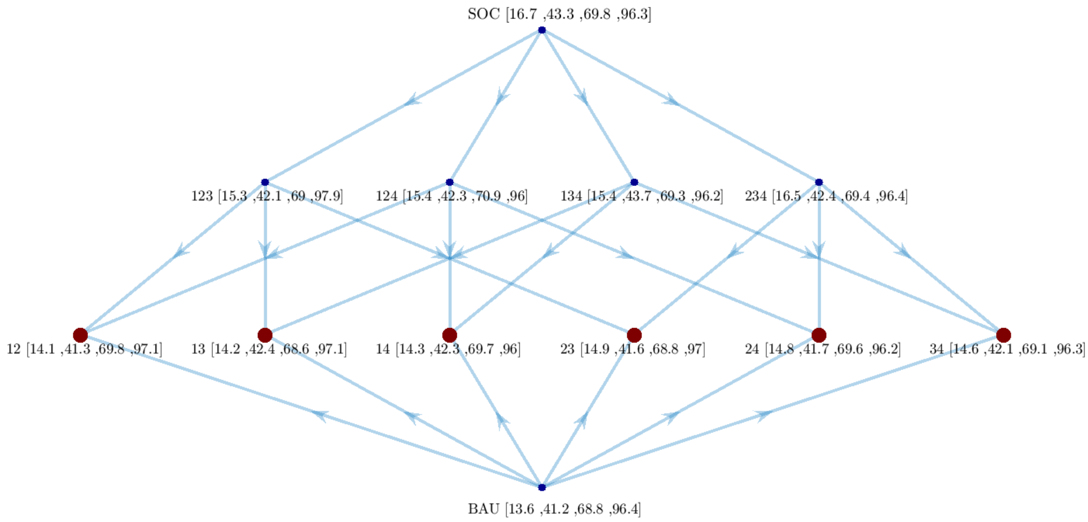
$$+\sum_{p\in C}\kappa_p\left(\sum_j \frac{t_j\omega_{jp}\psi_j^2}{\beta_j}\right) - \left(\frac{t_i\psi_i^2}{\beta_i}\right) - \left(\sum_{p\in C} \frac{\eta\psi_i\zeta_p + \beta_i\kappa_p(\sum_j \omega_{jp}\psi_j\chi_j)}{\beta_i}\right) = 0. \tag{16}$$

The same remarks given earlier apply. The reply functions given above determine tax rates and corresponding welfare levels for a given coalitions structure. These welfare levels in turn co-determine which coalitions are stable. How gains to cooperation are split among the coalition members finally determines the stability of a coalition.

3.2 Coalition stability and transfers

As discussed in the literature section, acknowledging jurisdiction heterogeneity complicates analysis of stable coalition size and introduces the question of composition. We follow the scheme used by Barrett [2001] and McGinty [2006]; first, coalition members are assigned the welfare they would obtain if they would defect from that coalition. An attractive property of this scheme is that it is compatible with individual rationality. A simple equal split for example, could result in outcomes in which a coalition between countries i and j is not formed even though country i can gain by making a higher transfer to country j which would induce it to join the coalition. Unlike McGinty, we cannot use the benefit-cost ratio of abatement to split the surplus, as these quantities are not specified directly in our model. We choose to split the surplus equally. As this scheme is a strong determinant of the outcomes, it is important to understand it thoroughly. In Figure 1, we show a graph describing all coalitions and transitions for a 4 country problem.

Figure 1: Graph of four country problem



Stable outcomes in red with stability defined as in Barrett [2001] and McGinty [2006]

The lines represent the transitions considered in this scheme. The arrow represents the direction of the transition. The numbers within brackets give the welfare levels before the split in one decimal place. The arrows are based on welfare levels after the split and the stability of the resulting coalition. For example, the transition from coalition structure {3,4} to {2,3,4} is infeasible because the after split welfare levels put a coalition member in disadvantage resulting to a defection to either {2,3}, {2,4}, or {3,4}. Because the stability of a coalition depends on the defection of any of the participants, arrows point to only one direction. This ensures no infinite loops occur. Note also that the graph does not describe a dynamic process, but shows how the internal stability of a g-sized coalition is dependent on the welfare levels of its participants under the $(g-1)$-sized subsets of that coalition that they are able to realize by unilaterally leaving the coalition. Countries 3 and 4 can join for a coalition in which, before a split, country 3 has a welfare of 69.06 and country 4 a welfare of 96.34. That is 0.24 more and 0.03 less welfare compared to their respective levels under the BAU case. The first step is to compensate country 4 for its loss in welfare making it indifferent between the coalition {3,4} and BAU. The surplus of 0.21 will be split equally between them, settling their rounded after-split welfare levels to 68.92 and 96.47. If, for example, coalition {1,3,4} is considered, country 1 compares its welfare to the welfare it would have if only country 3 and 4 are in a coalition, as this is the welfare it will obtain, keeping complement behaviour as fixed, should it defect from the coalition {1,3,4}. Contrasting this scheme to the general definition of coalition stability put forward by Bernheim et al. [1987], three major simplifications stand out. First, instead of coalition structures, only one coalition is considered at any point in time. The coalitions {1,2} and {3,4} could exist next to each other in real-life, but this possibility is not considered. Second, only defecting transitions are considered. If larger coalition forms are stable because no countries defect, then they enhance the welfare of their participants and hence the subset of smaller coalitions that can be formed from the coalition are by definition unstable. Third, only unilateral moves are considered. This should result in a status quo bias as a range of possibly rational moves are left out. Although no dynamic process is described, and stability of coalition structures is determined by calculating the whole graph, it's obvious the problem needs to be solved dynamically starting from BAU.

4 Simulations

Due to computational constraints, we limit our search to a (fixed) number of five countries. We choose this number of countries because the work of Eicher & Pethig suggests a stability gap between coalition sizes ranging from two to three or the grand coalition (for a small part of the parameter space). Choosing five countries holds some potential to reveal such discontinuities. Note however, that we are not exploring the same part of the parameter space as Eichner & Pethiq, as they considered cases of $n > 10$. Mean-preserving heterogeneity will be generated for each heterogeneous parameter p_i as follows

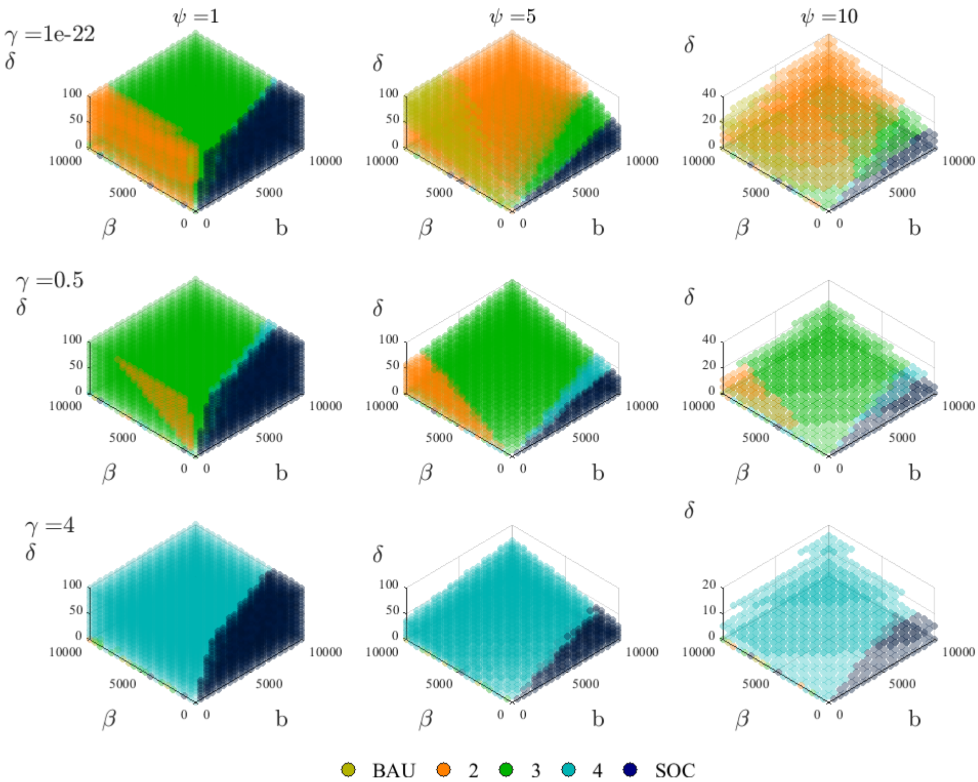
$$p_i = \bar{p} \frac{\frac{1}{\gamma} + (i-1)\gamma}{\frac{1}{N}\sum_i^N \left(\frac{1}{\gamma} + (i-1)\gamma\right)} \tag{17}$$

where γ denotes the degree of asymmetry. Countries with higher i's will have a higher than average p_i value. Note also that parameter values are always positive and asymmetry in absolute terms will rise with $\bar{p}$. As previous research has suggested the level of heterogeneity is of importance, we consider the homogeneous case ($\gamma = 1\mathrm{e}{-22}$), moderate heterogeneity ($\gamma = 0.5$) and strong heterogeneity ($\gamma = 4$). We set $\{\bar{k}_i,\, \alpha,\, a\} = \{1,\, 10000,\, 10000\}$, the same as Eichner and Pethig [2014b]. Capital stands in relation to emissions via ψ. Varying $\bar{k}$ will change the absolute interpretation of the other parameters. Also note that, α and a need to be high enough for the marginal benefit of consumption and production to be higher than the private marginal environmental damage for at least part of the range $k_i > 0$. If this condition is not satisfied, negative capital use and interest rates result. We explore the parameter space defined by $\{b,\, \beta,\, \delta,\, \psi,\, \gamma\}$. For a capital use of unity, $\beta > \alpha$ and $b > a$ imply negative marginal benefits to productivity and consumption. We therefore vary β and b from 0 to 10000. Note that this only guarantees that marginal benefits are zero at the mean level of capital use which may vary from country to country. Contrary to the literature reviewed, we use visual methods to describe outcomes in our parameter space. Coalition size included, we have six dimensions. We use three-dimensional scatter plots combined with color to capture four dimensions, using opacity levels to render it comprehensible on the page. The remaining two parameters ψ and γ are described by taking slices, resulting in nine three-dimensional scatter plots. The plots enable us to describe the outcomes more comprehensively. This includes sensitivity to interrelations between parameters; e.g. a relation between coalition size and a parameter need not be consistent for different values of the remaining parameters. We allow for negative taxes, but ignore outcomes for which negative emissions or a negative interest is observed.

4.1 Asymmetry in sensitivity to environmental change

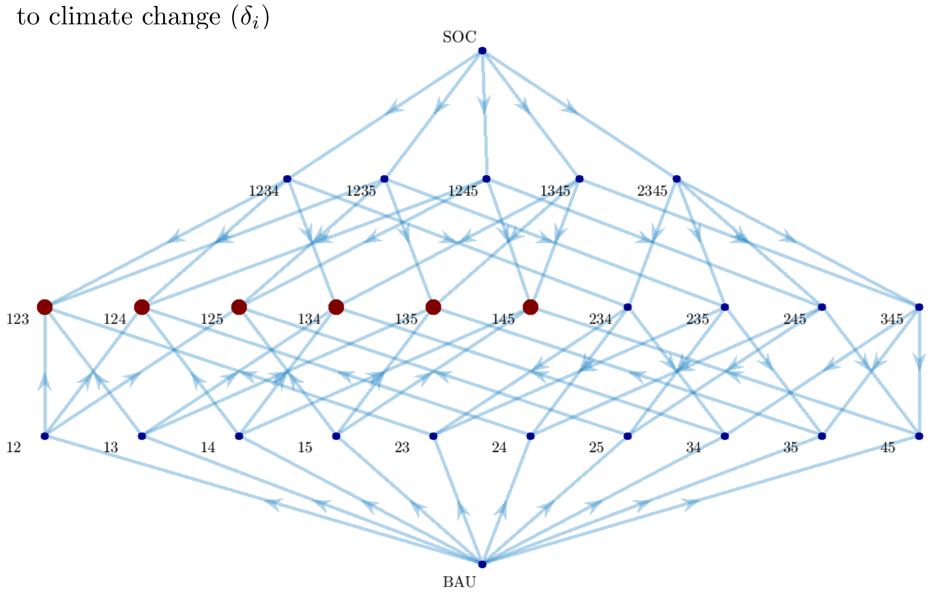
Differences in sensitivity to climate change can drive cooperation as some countries gain more from abatement than others, a benefit which can only be materialized through cooperation. The top three plots of Figure 2 represent the homogeneous case and clearly show the pattern described by Eichner and Pethig [2014b]. In the plots below, featuring increasing degrees of asymmetry, the figures alter significantly. In any figure the most salient result of Eichner & Pethig is reflected; the grand coalition is attained for parameter constellations for which benefits of cooperation are small. That is; high values of b and values of β, δ and ψ that are not too large. We remind the reader that higher b values mean that increasing shares of production and consumption are shifted to the second period such that the model approaches the case where total capital supply is fixed. β, negatively controlling how increasing capital affects marginal productivity, moderates this effect. We find that for higher levels of asymmetry in sensitivity to climate change, larger coalition sizes can be sustained also outside of this range, although still largely falling short of full cooperation. To get an idea of how stable coalition composition develops as the degree of asymmetry increases, we show transition graphs for two levels of asymmetry in Figure 3a and 3b.

Figure 2: Coalition sizes for asymmetric sensitivity to climate change (δ_i).



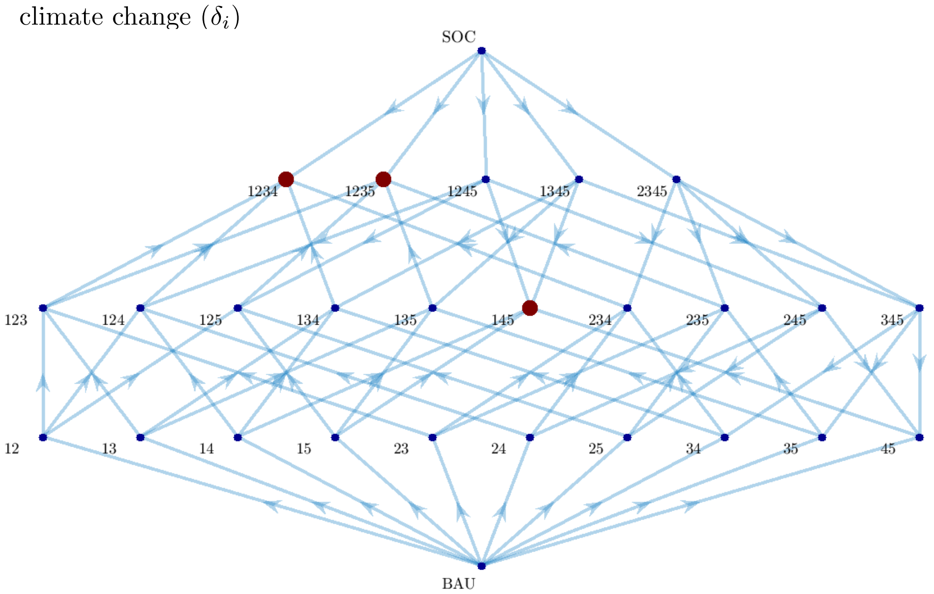
Colors describe the size of the largest stable coalition. β and b describe the rate at which marginal returns drop in industrial scale and private utility respectively. δ represents sensitivity to environmental damage. ψ represents the rate at which capital investments translate into environmental damage. γ represents the degree of asymmetry.

Figure 3a: Transition graph for moderate degrees of asymmetry (γ) in sensitivity to climate change (δ_i)



Red dots represent stable coalitions. Generated for $b = \beta = 3000$, $\psi = 5$, $\delta = 20$, $\gamma = .5$. Countries are, from left to right, increasingly sensitive to climate change.

Figure 3b: Transition graph for high degrees of asymmetry (γ) in sensitivity to climate change (δ_i)



Red dots represent stable coalitions. Generated for $b = \beta = 3000$, $\psi = 5$, $\delta = 20$, $\gamma = 4$. Countries are, from left to right, increasingly sensitive to climate change.

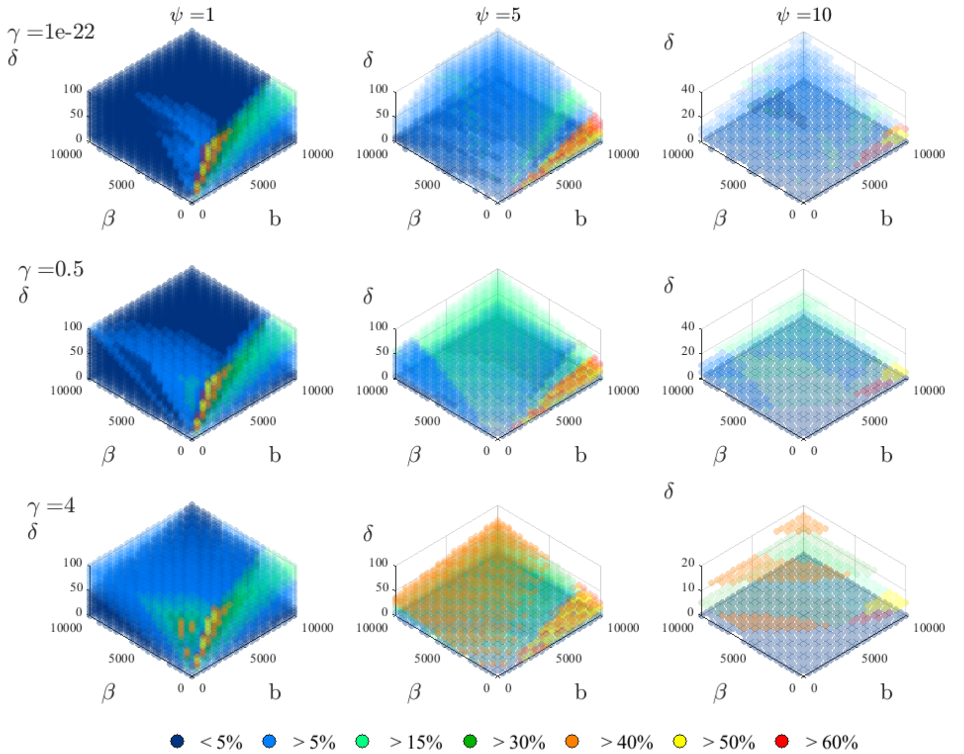
Table 2: Nash equilibrium quantities for a number of coalitions in Figure 3b.

coalition	taxes	interest	Domestic capital use	welfare before transfers
BAU	{0.60, 0.85, 1.10, 1.34, 1.59}	8.22	{0.49, 0.45, 0.41, 0.37, 0.32}	{-, -, -, -, -}
C = {1,2}	{1.42, 1.42, 1.09, 1.35, 1.61}	8.15	{0.38, 0.38, 0.43, 0.39, 0.35}	{0.24, 0.58, 1.32, 1.51, 1.69}
C = {4,5}	{0.47, 0.73, 0.99, 2.77, 2.77}	8.11	{0.55, 0.51, 0.46, 0.17, 0.17}	{1.52, 1.84, 2.15, -0.07, 0.53}
C = {1,4,5}	{3.20, 0.68, 0.97, 3.20, 3.20}	7.94	{0.15, 0.57, 0.53, 0.15, 0.15}	{-0.42, 4,52, 5.25, 2.35, 2.37}
C = {1,2,3,5}	{3.49, 3.49, 3.49, 1.27, 3,49}	7.74	{0.17, 0.17, 0.17, 0.54, 0.17}	{1.19, 2.44, 3.75, 9.52, 6.52}
SOC	{4.05, 4.05, 4.05, 4.05, 4.05}	7.48	{0.16, 0.16, 0.16, 0.16, 0.16}	{2.34, 3.95, 5.61, 7.33, 9.10}

Generated for $b = \beta = 3000$, $\psi = 5$, $\delta = 20$, $\gamma = 4$. Welfare levels are the remainder after subtraction BAU welfare levels. Countries are, from left to right, decreasingly sensitive to climate change.

Table 2 supplements Figure 3b with some quantities of interest for a number of coalition structures. We find that large stable coalitions always consist of one of the countries that are most sensitive to climate change. The larger coalitions often do not contain both sensitive countries. All other things equal, the quadratic environmental damage function implies that benefits to free-riding rise as the number of signatories to a coalition increase. By directly partnering with the other extreme, keeping other sensitive countries outside the coalition, free-riding behaviour by non-signatories is less strong and overall benefit of cooperation higher. From coalitions $\{4,5\}$ and $\{1,4,5\}$ in Table 2, it is also clear that transfers play an important role in establishing stable coalitions. Country 1 is substantially worse off before transfers compared to the coalition it would realize ($\{4,5\}$) by unilaterally defecting from $\{1,4,5\}$. In Figure 4 we show the highest level of abatement found for stable coalition structures. It is clear that for higher levels of asymmetry also more abatement is realized compared to the BAU scenario. The degree of abatement depends largely on the rate at which invested capital causes emissions (ψ). Contrasting Figure 4 to Figure 5 also makes clear that the size of the largest stable coalition is a fairly good indicator of the degree of realized abatement, but not everything can be explained by this feature alone. Substantial abatement differences exist for regions of the parameter space for which the largest stable coalition is of equal size.

Figure 4: Abatement levels for asymmetric sensitivity to climate change (δ_i)

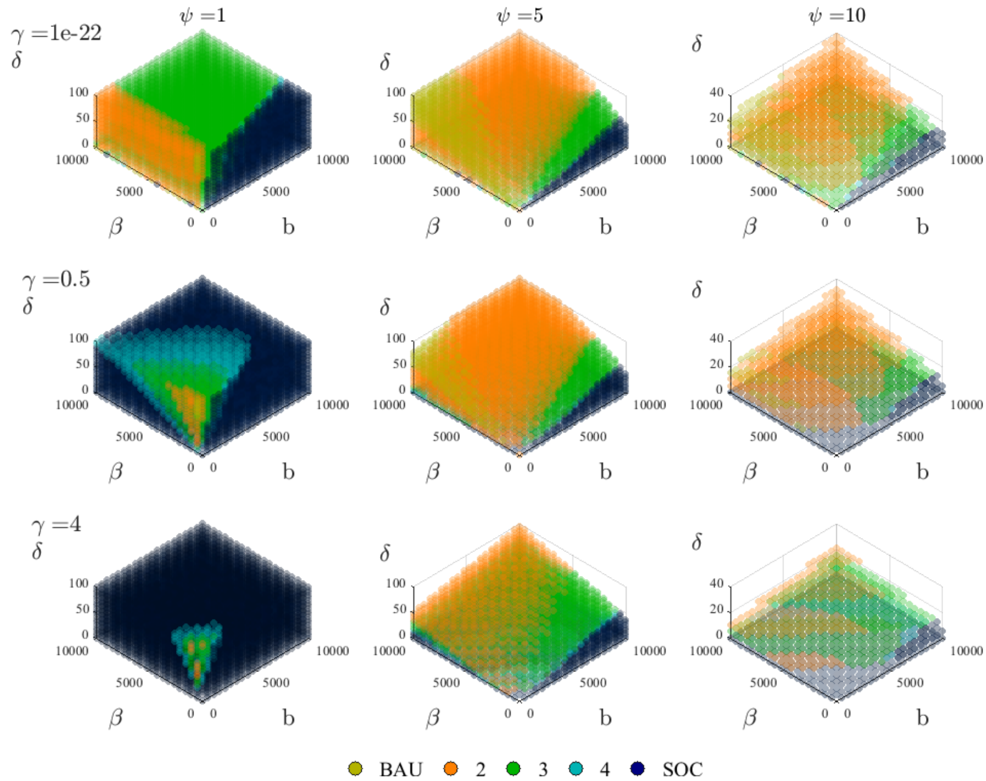


Colors describe the size of the largest stable coalition. β and b describe the rate at which marginal returns drop in industrial scale and private utility respectively. δ represents sensitivity to environmental damage, ψ represents the rate at which capital investments translate into environmental damage. γ represents the degree of asymmetry.

4.2 Asymmetry in capital endowments

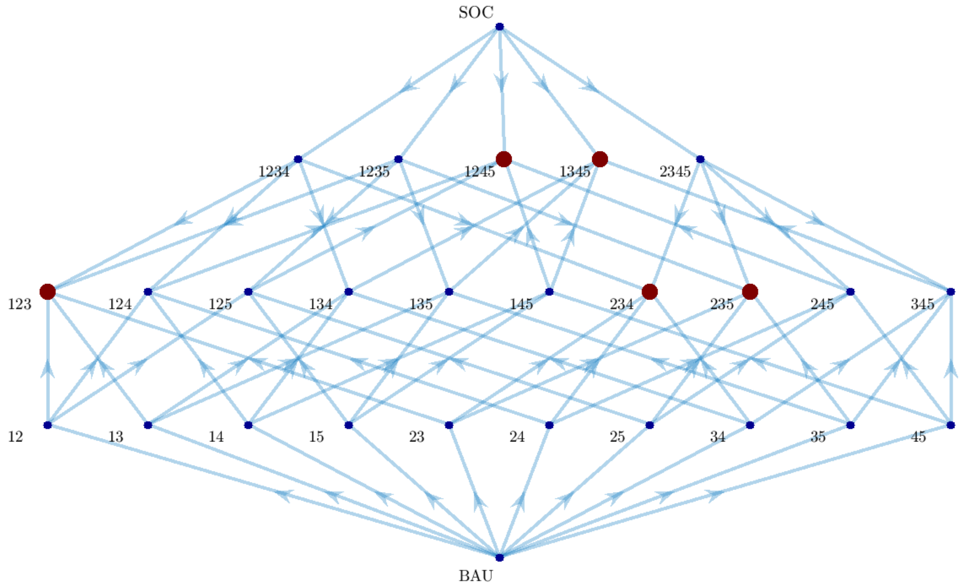
The height of taxes can also be used to affect the terms of trade. For example, through higher taxes, poor countries, who import capital, can ensure that a larger part of profits stay in their country both in the form of tax revenue and through lower interest payments as the interest rate is negatively affected by tax increases. Of course, higher taxes also cause less capital to be invested in their country resulting in lower overall profit. The ultimate result is an inefficient equilibrium capital allocation which means there are more benefits to be gained from cooperation. In Figure 5 we show the largest stable coalitions. We indeed find more cooperation with increasing degrees of asymmetry, especially when the transition rate from capital to emissions (ψ) and the sensitivity to climate change (δ) are low. We note that high values of δ are no clear obstacle to cooperation when countries differ in their sensitivity to climate change (see Chapter 4.1). The transition graph of Figure 6 in combination with Table 3 provides more insight in the forces behind this result. The large stable coalitions contain both rich countries. We draw attention to differences in strategic behaviour in Table 3.

Figure 5: Coalition sizes for asymmetric capital endowments ($\bar{k}_i$).



Colors describe the size of the largest stable coalition. β and b describe the rate at which marginal returns drop in industrial scale and private utility respectively. δ represents sensitivity to environmental damage, ψ represents the rate at which capital investments translate into environmental damage. γ represents the degree of asymmetry.

Figure 6: Transition graph for a moderate degree of asymmetry in capital endowments ($\bar{k_i}$)



Red dots represent stable coalitions. Generated for $b = \beta = 2000$, $\psi = 1$, $\delta = 50$, $\gamma = .5$. Countries are, from left to right, increasingly well endowed, with country 3 being averagely endowed.

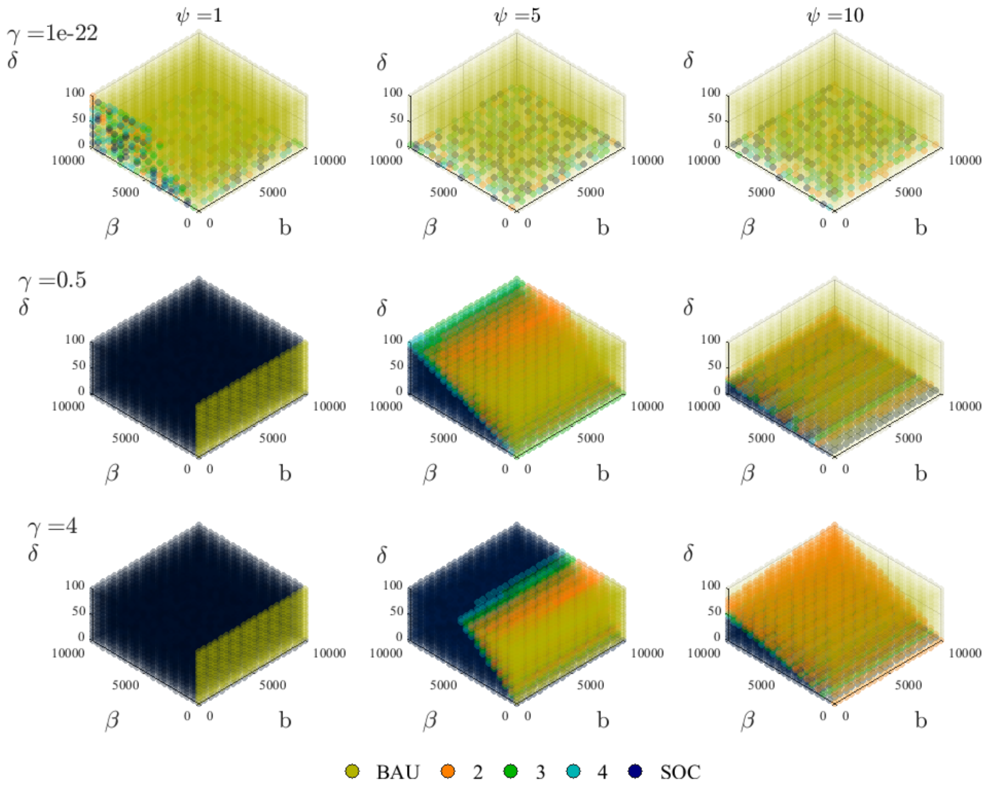
Table 3: Nash equilibrium quantities for a number of coalitions in Figure 6.

Coalition	taxes	interest	domestic capital use	welfare before transfers
BAU	{1.8, 1.2, 0.7, 0.1, -0.5}	9.10	{0.51, 0.53, 0.55, 0.57, 0.59}	{-, -, -, -, -}
C = {1,2}	{2.3, 2.3, 0.7, 0.4, 0.1}	9.08	{0.46, 0.46, 0.56, 0.58, 0.60}	{7.5, 1.2, 8.8, 4.5, 0.3}
C = {4,5}	{1.2, 1.0, 0.7, 0.5, 0.5}	9.10	{0.52, 0,54, 0.56, 0.57, 0.57}	{2.5, 1.9, 1.3, 0.6, -0.3}
C = {1,2,3}	{3.1, 3.1, 3.1, 0.5, 0.2}	9.02	{0.44, 0.44, 0.44, 0.62, 0.64}	{26.4, 13.0, -0.6, 13.5, 1.9}
C = {1,3,4,5}	{3.1, 1.1, 3.1, 3.1, 3.1}	8.99	{0.47, 0.60, 0.47, 0.47, 0.47}	{48.6, 48.5, 14.5, -1.7, -17.3}
SOC	{4.8, 4.8, 4.8, 4.8, 4.8}	8.76	{0.38, 0.38, 0.38, 0.38, 0.38}	{99.0, 62.9, 27.5, -7.5, -41.9}

Values generated for $b = \beta = 2000$, $\psi = 1$, $\delta = 50$, $\gamma = .5$. Countries are, from left to right, increasingly well endowed, with country 3 being averagely endowed. Welfare levels are the remainder after subtraction BAU welfare levels

A raise in taxes by coalition {1,2} causes a tax raise by countries 4 and 5. Tax raises by the coalition {4,5} however, cause countries 1 and 2 to lower their taxes. This means that in this case taxes are strategic complements for the rich countries and strategic substitutes for the poor countries. Higher taxes from rich countries cause an influx of capital in the poor countries and a decrease in the global capital stock and hence emissions. This means that the environmental marginal benefit of taxation is lower, as the environmental damage function is quadratic, which warrants lower taxes. Clearly, for poor countries, the change in marginal benefit from affecting the terms of trade in their favour increases stronger and vice versa for the rich countries. From the SOC scenario in Table 3, it is clear that, before transfers, the poor countries benefit the most from cooperation. This should not be surprising; in the resulting equilibria, the poor countries import a relatively large amount of capital the interest payments of which they get to tax against high tariffs. The environmental benefit of reduced abatement comes on top of this and is equal for all countries. Hence, transfers from poor to rich countries are needed to make these coalitions self-enforcing. The question arises to what extent coalition formation would have arisen purely for reasons of tax competition. In Figure 6 we show the largest coalition size for the situation in which environmental damage is local ($\omega_{ij} = 1 \; \forall \; i = j$, $\omega_{ij} = 0 \; \forall \; i \neq j$). Note this is not exactly the same as the case for which $\delta = 0$. In the current case ($\delta \neq 0$), environmental damage still acts as an incentive to reduce emissions for each country. In the absence of spillovers however, there is no externality to solve. We see that for high β values and asymmetric capital endowments ($\bar{k_i}$), a large degree of cooperation can already be assured. Contrasting Figure 5 to Figure 7 shows that the environmental externality breaks down cooperation in some scenarios while improving it in others.

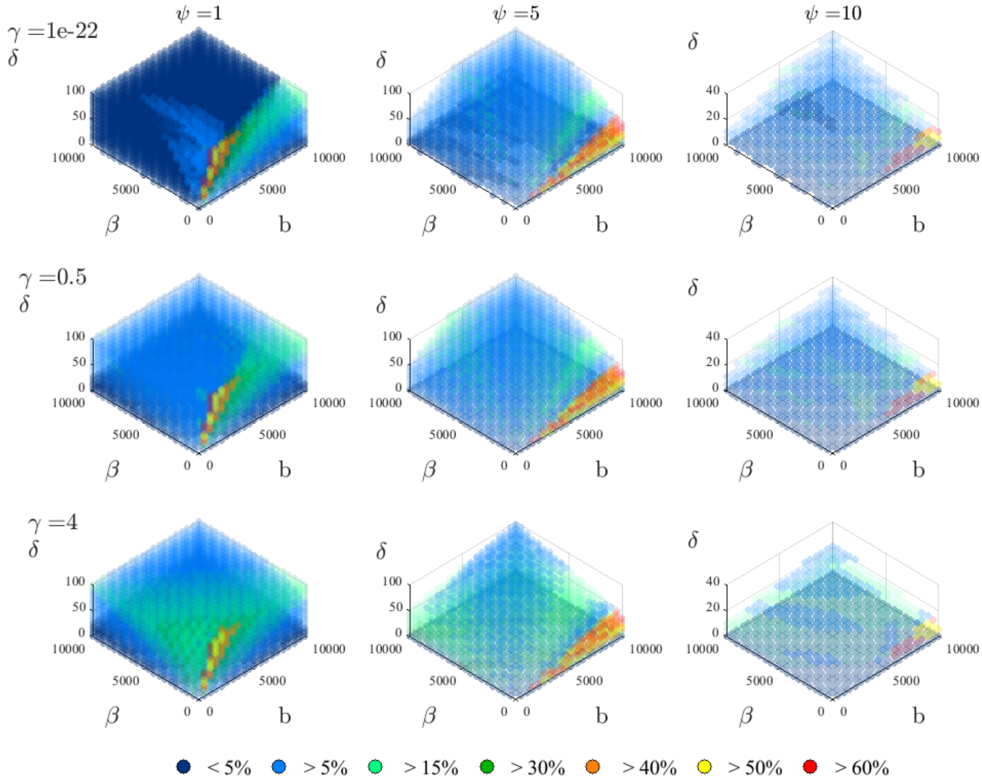
Figure 7: Coalition sizes for asymmetric capital endowments ($\bar{k_i}$) and local pollution ($\omega_{ij} = 0, \; \forall \; j \neq i$)



Colors describe the size of the largest stable coalition. β and b describe the rate at which marginal returns drop in industrial scale and private utility respectively. δ represents sensitivity to environmental damage, ψ represents the rate at which capital investments translate into environmental damage. γ represents the degree of asymmetry.

Cooperation is stifled for high levels of δ and β, but improved for scenarios with low β's and high b's. This insight helps to understand the cone-like shape seen in Figure 5 for $\psi = 1$, $\gamma = 0.5$. In that case, incentives to cooperate to remedy tax competition are strong enough to ensure full cooperation for high values of δ and β and environmental concerns dominate the area with low values of β's and high b. Figure 8 shows that for higher degrees of asymmetry in capital endowments, relative abatement levels also improve compared to BAU. In some cases even more so than in the case countries differ in sensitivity to climate change (δ_i). However, abatement is markedly lower when the transition rate from capital to emissions (ψ) is high.

Figure 8: Abatement levels for asymmetric capital endowments ($\bar{k_i}$).

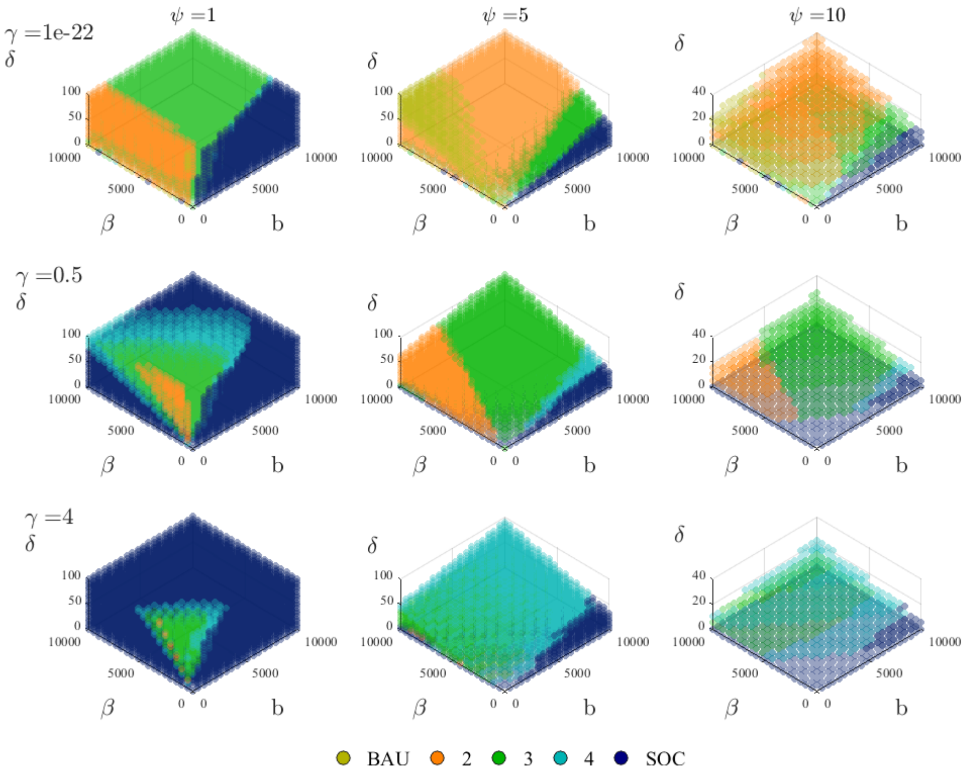


Colors describe the reduction of emissions compared to the BAU case. β and b describe the rate at which marginal returns drop in industrial scale and private utility respectively. δ represents sensitivity to environmental damage, ψ represents the rate at which capital investments translate into environmental damage. γ represents the degree of asymmetry.

4.3 Positive covariance between capital endowments and sensitivity to climate change

Here, we consider the case in which asymmetry in capital endowments and sensitivity to climate change are positively corelated (i.e. the richer countries 4 and 5 are also more sensitive to climate change). Whether positive covariance between sensitivity to climate change and capital endowments is a reasonable reflection of reality we do not mean to answer here. Rich countries, with more infrastructure in place, have more material prospects to lose. On the other hand, poor countries might not be economically strong enough to deal with the consequences of global warming putting basic human needs at risk. We leave this assessment to the reader. Our main purpose here is to get an idea of how the previously demonstrated effects of heterogeneity interact with each other.

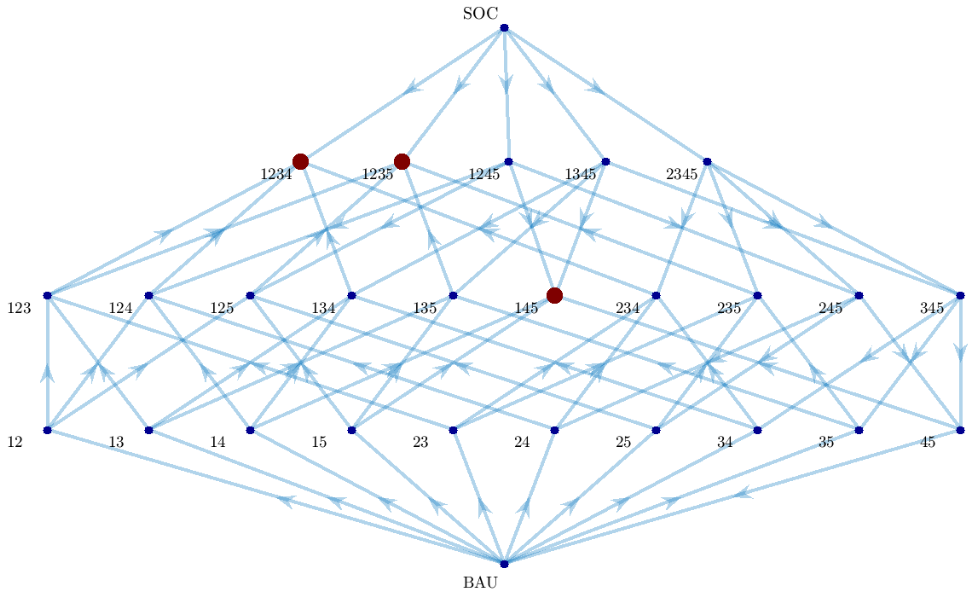
Figure 9: Coalition sizes for positive covariance in asymmetric sensitivity to climate change (δ_i) and capital endowments ($\bar{k_i}$).



Colors describe the size of the largest stable coalition. β and b describe the rate at which marginal returns drop in industrial scale and private utility respectively. δ represents sensitivity to environmental damage, ψ represents the rate at which capital investments translate into environmental damage. γ represents the degree of asymmetry.

We do stress that covariance here can not be caused by perception of value of environmental quality (e.g. the rich value the environment more). The model has inhabitants with identical utility functions. A model reflecting any such assumption should include a utility structure in which the utility from environmental quality is a function of income/endowments. The stability of coalitions for this case, shown in Figure 9, is a mix of the stability outcomes found in section 4.1 and 4.2. The grand coalition is often stable for low transition rates ψ, as was the case for asymmetric capital endowments, but looks more like the figures for asymmetric sensitivities to climate change (δ_i) with less cooperation for low values of b. In Figure 10 and Table 4, we show a transition graph for a high degree of asymmetry.

Figure 10: Transition graph for a high degree of asymmetry in both sensitivity to climate change (δ_i) and capital endowments ($\bar{k_i}$) with positive covariance.



The richer countries 4 and 5 are also more sensitive to climate change. Red dots represent stable coalitions. Generated for $b = \beta = 5000$, $\psi = 5$, $\delta = 40$, $\gamma = 4$.

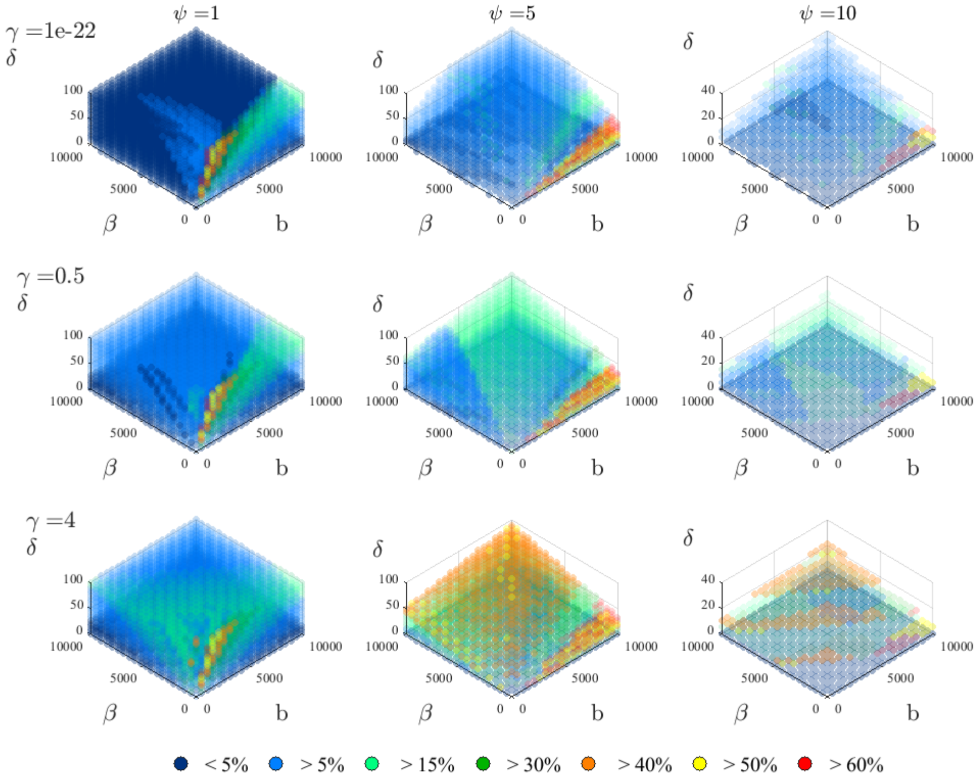
Table 4: Nash equilibrium quantities for a number of coalitions in Figure 10.

Coalition	taxes	interest	domestic capital use	welfare before redistribution
BAU	{-0.1, 0.8, 1.7, 2.7, 3.7}	7.05	{0.60, 0.51, 0.41, 0.32, 0.22}	{-, -, -, -, -}
C = {1,2}	{0.7, 0.7, 1.8, 2.8, 3.8}	7.01	{0.52, 0.52, 0.42, 0.32, 0.22}	{0.4, 0.8, 1.0, 1.2, 1.3}
C = {4,5}	{-0.8, 0.3, 1.3, 5.6, 5.6}	6.90	{0.69, 0.59, 0.49, 0.06, 0.06}	{1.7, 2.8, 3.7, -1.9, 0.3}
C = {1,4,5}	{6.1, 0.4, 1.6, 6.1, 6.1}	6.49	{0.10, 0.66, 0.54, 0.10, 0.10}	{-0.2, 1.0, 1.2, 0.7, 1.0}
C = {1,2,3,5}	{5.9, 5.9, 5.9, 3.2, 5.9}	6.15	{0.18, 0.18, 0.18, 0.45, 0.18}	{0.4, 0.6, 1.0, 2.0, 1.8}
SOC	{7.1, 7.1, 7.1, 7.1, 7.1}	5.71	{0.14, 0.14, 0.14, 0.14, 0.14}	{0.7, 0.9, 1.3, 1.6, 2.0}

Generated for $b = \beta = 5000$, $\psi = 5$, $\bar{\delta_i} = 40$, $\gamma = 4$. The richer countries 4 and 5 are also more sensitive to climate change. Red dots represent stable coalitions. Welfare levels are the remainder after subtraction BAU welfare levels

In Table 4 we can see that in the BAU case, capital use is much higher in poor countries with low sensitivity to climate change. In general the game described in Figure 10 and Table 4, is very similar to the game described in section 4.1 as climate change arguments dominate the game for high values of (ψ). This also explains the similarity of Figure 2 and Figure 9 for high values of ψ. Not surprisingly, transition graphs for lower values of ψ, left out here, look much more like those found under asymmetric capital endowments. In Figure 11 we see more relative abatement than in the case only sensitivities to climate change (δ_i) differ. Keep in mind however that this is compared to the BAU case. In the BAU scenario poor countries have an incentive to keep taxes high to improve their terms of trade resulting in an inefficient allocation of capital and a smaller global capital stock.

Figure 11: Abatements levels for positive covariance in asymmetric sensitivity to climate change ($\bar{\delta_i}$) and capital endowments ($\bar{k_i}$)

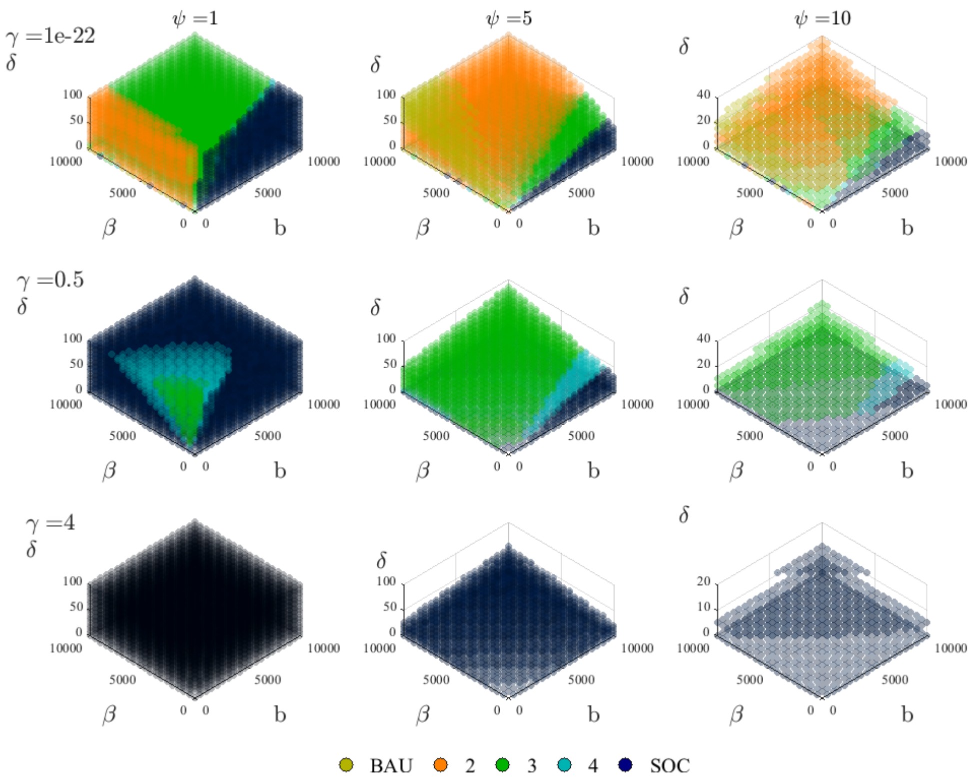


Colors describe the reduction of emissions compared to the BAU case. β and b describe the rate at which marginal returns drop in industrial scale and private utility respectively. δ represents sensitivity to environmental damage, ψ represents the rate at which capital investments translate into environmental damage. γ represents the degree of asymmetry.

4.4 Negative covariance between capital endowments and sensitivity to climate change

Here, we consider the case in which asymmetry in capital endowments and sensitivity to climate change are negatively corelated (i.e. richer countries 1 and 2 are less sensitive to climate change). Richer countries already have an incentive to keep taxes low to prevent taxation on the interest of their capital. A relatively low sensitivity to climate change only adds to this. Surprisingly, we find the highest degree of cooperation of all scenarios considered (see Figure 12). To understand why, we again rely on an example in the form of a transition graph (see Figure 13).

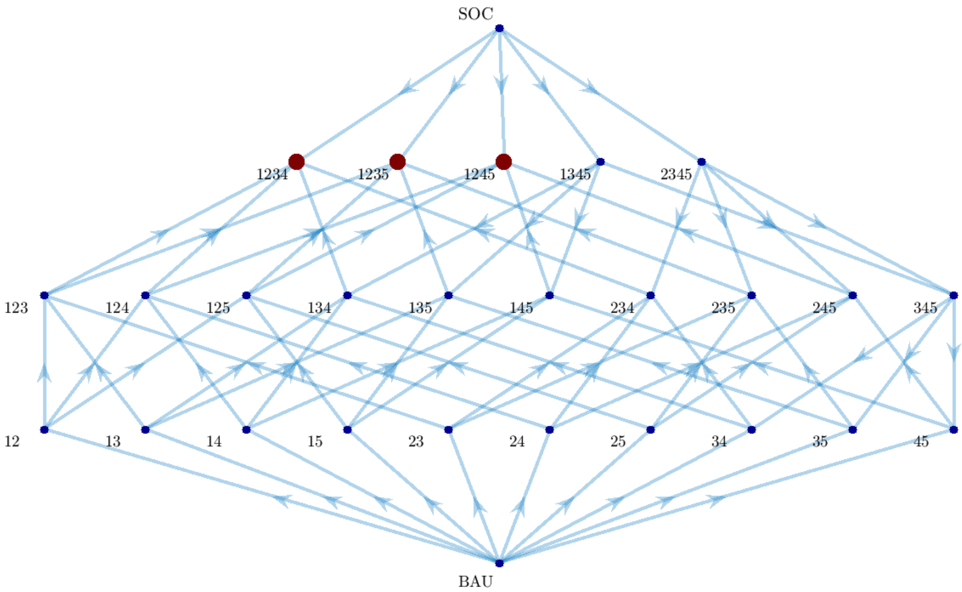
Figure 12: Coalition sizes for negative covariance between sensitivity to climate change (δ_i) and capital endowments ($\bar{k_i}$)



Colors describe the size of the largest stable coalition. β and b describe the rate at which marginal returns drop in industrial scale and private utility respectively. δ represents sensitivity to environmental damage, ψ represents the rate at which capital investments translate into environmental damage. γ represents the degree of asymmetry.

In Table 5 , although going from BAU to {1,2} affects the welfare of jurisdictions 4 and 5 greatly (negatively), the tax rates of 4, and 5 stay (almost) the same. Put differently, the slope of their reply function w.r.t. taxes t_1 and t_2 is (almost) flat. This means that the changes in marginal benefits of their taxes due to being on a different part of the climate damage function, which would lead them to lower their taxes, are offset by a deterioration of their terms of trade (discussed in more detail in the model section). In coalition {1,2,5}, before redistribution, country 5 gains a bit compared to the BAU case. After redistribution (not shown in table) however, jurisdiction 5 is less well off than in the BAU case. However, its welfare gain w.r.t. to the {1,2} case is still very large. It cannot defect from the coalition is not an option as the conditions it would receive otherwise are much worse.

Figure 13: Transition graph for a high degree of asymmetry in both sensitivity to climate change (δ_i) and capital endowments ($\bar{k_i}$) with negative covariance.



In this case, the richer countries, 1 and 2, are also less sensitive to climate change. Transition graphs for low and high degrees of asymmetry in sensitivity to climate change (δ_i) respectively. Red dots represent stable coalitions. Generated for $b = \beta = 5000$, $\psi = 5$, $\delta = 20$, $\gamma = .5$

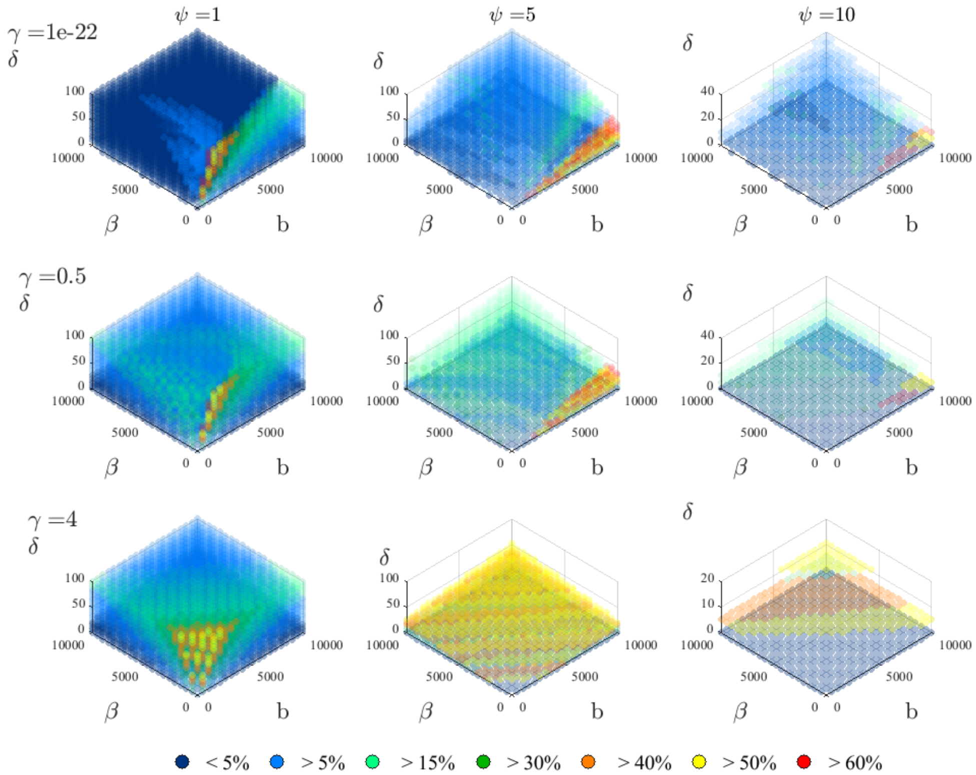
Table 5: Nash equilibrium quantities for a number of coalitions in Figure 13.

	taxes	interest	domestic capital use	welfare before redistribution
BAU	{-0.5, 0.3, 1.1, 1.9, 2.7}	7.23	{0.60, 0.53, 0.45, 0.37, 0.29}	{-, -, -, -, -}
C = {1,2}	{-0.2, -0.2, 1.1, 1.9, 2.7}	7.24	{0.57, 0.57, 0.44, 0.36, 0.25}	{7.0, -3.5, -11.2, -17.6, -23.9}
C = {4,5}	{-0.7, 0.1, 1.0, 4.4, 4.4}	7.04	{0.66, 0.58, 0.50, 0.15, 0.15}	{-0.4, 1.0, 2.4, -0.4, 1.8}
C = {1,5}	{2.4, 0.4, 1.2, 2.0, 2.4}	7.09	{0.34, 0.55, 0.47, 0.38, 0.34}	{-1.6, 0.7, 1.7, 2.6, 4.1}
C = {1,2,5}	{2.8, 2.8, 1.2, 2.1, 2.8}	6.92	{0.34, 0.34, 0.49, 0.41, 0.34}	{-2.3, -0.3, 3.6, 5.6, 7.7}
C = {1,4,5}	{4.2, 0.3, 1.1, 4.2, 4.2}	6.80	{0.22, 0.62, 0.53. 0.22, 0.22}	{-5.0, 2.3, 5.1, 4.4, 8.2}
C = {1,2,3}	{1.0, 1.0, 1.0, 2.0, 2,8}	7.12	{0.48, 0.48, 0.48, 0.38, 0.30}	{-0.4, 0.4, 1.4, 2.0, 2.7}
C = {1,2,3,5}	{3,9, 3.9, 3.9, 2.1, 2.9}	6.62	{0.29, 0.29, 0.29, 0.47, 0.29}	{-0.4, -0.1, 0,4, 1.1, 1.3}
SOC	{5.6, 5.6, 5.6, 5.6, 5.6}	6.11	{0.22, 0.22, 0.22, 0.22, 0.22}	{-.0.8, -0.2, 0.6, 1.3, 2.1}

Generated for $b = \beta = 5000$, $\psi = 5$, $\delta = 20$, $\gamma = .5$. In this case, the richer countries, 4 and 5, are also less sensitive to climate change. Welfare levels are the remainder after subtraction BAU welfare levels

Similarly, both country 3 and 5 can choose to leave coalition {1,2,3,5} but whoever is left, will be in deadlock. In any case, countries 3, 5 or both will have to pay in order to prevent the situation in which 1,2 form a coalition. This result paints a rather grim picture for poor countries with high sensitivity to climate change. Their lack of financial resources can be exploited by rich countries by threatening to form coalitions under which their conditions will be even worse. This example also illustrates well the implications of the system of welfare transfers employed in our model. Although stability of any coalition is dominated by the cooperative gains w.r.t. BAU, the actual transfers for a coalition of size g are strongly dependent on the welfare levels of the $g-1$ size subsets of that coalition.

Figure 14: Abatements levels for negative covariance between sensitivity to climate change (δ_i) and capital endowments ($\bar{k_i}$).



Colors describe the reduction of emissions compared to the BAU case. β and b describe the rate at which marginal returns drop in industrial scale and private utility respectively. δ represents sensitivity to environmental damage, ψ represents the rate at which capital investments translate into environmental damage. γ represents the degree of asymmetry.

The upside of this striking result is that relative abatement levels are higher than for any other scenario considered (see Figure 14). In effect, rich countries 'solve' the environmental problems of poor countries but demand retribution in the form of transfers. However, looking at absolute abatements levels, figures left out for parsimony, show that abatement is almost the same with only slightly higher abatement in the negative covariance scenario. This is because BAU emissions are already lower. In the BAU case, rich countries have (very) low tax rates and poor countries (very) high tax rates. As marginal economic returns to capital decrease per country, overall returns drop with a lower capital stock and emissions as a result. Note that this is true for any tax-rate composition that is non-uniform across countries, but it is especially pronounced for the present case.

5 Conclusion

In this paper we assessed whether accounting for heterogeneity of countries in capital endowments and sensitivity to climate change affects the existence of self-enforcing IETAs. As past literature using partial-equilibrium models did not answer the question satisfactorily for a tax competition setting, we adapted the homogeneous general-equilibrium model used by Eichner and Pethig [2014b]. Accounting for heterogeneity increases complexity considerably and additional assumptions on the possible coalition structures and formation process are needed to yield tractable results. Naturally, the results are therefore bound up with these choices. We used a stability concept similar to the ones employed by Barrett [2001] and McGinty [2006]. The most appealing quality of their method is that profitable coalition deviations are always taken advantage of which corresponds to individual rational behaviour. We ran simulations with five countries for a large parameter space using mean-preserving heterogeneity. We find improvements in cooperation and abatement both in the case of asymmetric sensitivity to climate change and in the case of asymmetric capital endowments. Cooperation and abatement improve even further when both quantities are asymmetrically distributed over countries. Relative abatement is highest in the scenario in which capital endowments and sensitivity to climate change are negatively correlated. However, absolute abatement is roughly similar to the positive covariance case as emission levels are already lower without cooperation for the negative covariance scenario. Composition of coalitions in the presence of asymmetry in sensitivity to climate change is dominated by a simple result: if benefits to free-riding rise as the number of signatories to the coalition increase, it's more beneficial to partner up to the other extreme of the spectrum directly, leaving countries with lower benefits to free-riding outside the coalition. In the case of asymmetric capital endowments, the largest coalitions consist of both rich countries. Transfers play a large role in ensuring coalition stability in both cases. In case of asymmetric capital endowments, transfers even induces rich countries to form coalitions with poor countries that would otherwise be strongly unfavorable to them compared to the non-cooperative scenario. Finally, we find that if poor countries are more sensitive to climate change, rich countries can exploit this by threatening to form coalitions that are damaging to poor countries. In the resulting stable coalitions, poor countries are less well off than without cooperation but unilaterally defecting from these coalitions results in conditions that are even worse. As mentioned before however; these coalitions do result in the most relative abatement. Future research could focus on different sources of heterogeneity. The current model already provides ample room to do so as well as the ability to assess the effect asymmetric spillovers have on self-enforcing coalitions and abatement. Another topic of future research could be the effect the distribution of heterogeneity has on results. An evaluation of the empirically most appropriate distribution for different kinds of asymmetries can further aid in identifying relevant obstacles to cooperation.

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Appendix A

Before writing down the reply functions, we derive some intermediary quantities to be substituted later.

Savings

To deduce the first equality in Equation (7), we sequentially substitute the functional forms and the first and second period budget constraint into the utility function which yields the following complete utility function.

$$U_i = a_i(\bar{k_i} - s_i) - \frac{b_i}{2}(\bar{k_i} - s_i)^2 + (1+r)s_i + \pi_i + t_i\psi_i k_i \tag{A.1}$$

Note that citizens are assumed not to take account of emissions when deciding on their consumption allocation. Setting the first derivative w.r.t. s_i equal to zero

$$U_{s_i} = -a_i - b_i(\bar{k_i} + s_i) + 1 + r = 0. \tag{A.2}$$

Rewriting Equation (A.2) w.r.t. s_i yields the first equality in Equation (7)

Capital employed

To deduce the second equality in equation (7), we write down the f.o.c. of country i's profit function. It's important to keep the coding of the ω_{ji}, ψ_j, and t_j in mind. t_j is a tax on each unit of emission in country j which is emitted in a proportion ψ_j of capital use k_j. The transition rate ψ_k therefore determines at what rate t_k functions as a tax on capital. ω_{ij} regulates to what degree this damage is felt across countries but does not affect the definition of t_j which is still a tax on all emissions in country j. Therefore we do not see ω_{ji} coming back in the f.o.c. of profit maximization.

$$\pi_i = \alpha_i - \frac{\beta_i}{2}k_i^2 - (1 + r + t_i\psi_i)k_i \tag{A.3}$$

Setting the first derivative w.r.t. k_i equal to zero

$$\frac{\partial \pi_i}{\partial k_i} = \alpha_i - \beta_i k_i - (1 + r + t_i\psi_i) = 0. \tag{A.4}$$

Rewriting Equation (A.4) w.r.t. k_i yields the second equality in Equation (7).

Global interest rate

To deduce the equality of Equation (8), we insert the expressions for s_i and k_i of Equation (7) in the market clearing condition yields

$$\sum_j \left(\frac{1 - a_j + r}{b_j} + \bar{k_j} \right) = \sum_j \left(\frac{\alpha_j - 1 - r - t_j\psi_j}{\beta_j} \right). \tag{A.5}$$

Rewriting:

$$\sum_j \left(\frac{r}{b_j} + \frac{r}{\beta_j} \right) = \sum_j \left(\frac{\alpha_j - 1 - t_j\psi_j}{\beta_j} - \frac{1 - a_j}{b_j} - \bar{k_j} \right) \tag{A.6}$$

$$r\sum_j\left(\frac{b_j+\beta_j}{b_j\beta_j}\right)=\sum_j\left(\frac{(\alpha_j-1-t_j\psi_j)b_j-(1-a_j)\beta_j}{b_j\beta_j}-\bar{k_j}\right) \tag{A.7}$$

Defining

$$\eta=\left(\sum_j\left(\frac{b_j+\beta_j}{b_j\beta_j}\right)\right)^{-1} \tag{A.8}$$

yields equation (8).

Capital export

Substituting the interest rate in the expressions for savings and capital we find

$$s_i=\frac{1-a_i}{b_i}+\frac{\eta}{b_i}\sum_j\left(\frac{(\alpha_j-1-t_j\psi_j)b_j-(1-a_j)\beta_j}{b_j\beta_j}-\bar{k_j}\right)+\bar{k_i}$$

$$=\frac{1-a_i}{b_i}+\frac{\eta}{b_i}\sum_j\left(\frac{(\alpha_j-1)b_j-(1-a_j)\beta_j}{b_j\beta_j}-\bar{k_j}\right)-\frac{\eta}{b_i}\left(\sum_j\frac{t_j\psi_j}{\beta_j}\right)+\bar{k_i} \tag{A.9}$$

$$k_i=\frac{\alpha_i-1}{\beta_i}-\frac{\eta}{\beta_i}\sum_j\left(\frac{(\alpha_j-1-t_j\psi_j)b_j-(1-a_j)\beta_j}{b_j\beta_j}-\bar{k_j}\right)-\frac{t_i\psi_i}{\beta_i}$$

$$=\frac{\alpha_i-1}{\beta_i}-\frac{\eta}{\beta_i}\sum_j\left(\frac{(\alpha_j-1)b_j-(1-a_j)\beta_j}{b_j\beta_j}-\bar{k_j}\right)+\frac{\eta}{\beta_i}\left(\sum_j\frac{t_j\psi_j}{\beta_j}\right)-\frac{t_i\psi_i}{\beta_i} \tag{A.10}$$

Therefore capital export of country i is

$$(s_i-k_i)=\frac{1-a_i}{b_i}-\frac{\alpha_i-1}{\beta_i}+\eta\left(\frac{b_i+\beta_i}{b_i\beta_i}\right)\left(\sum_j\frac{(\alpha_j-1)b_j-(1-a_j)\beta_j}{b_j\beta_j}-\bar{k_j}\right)+\bar{k_i}$$

$$-\eta\left(\frac{b_i+\beta_i}{b_i\beta_i}\right)\left(\sum_j\frac{t_j\psi_j}{\beta_j}\right)+\frac{t_i\psi_i}{\beta_i} \tag{A.11}$$

We define the the part not dependent on taxes as ζ_i, such that

$$(s_i-k_i)=\zeta_i-\eta\left(\frac{b_i+\beta_i}{b_i\beta_i}\right)\left(\sum_{j\neq i}\frac{t_j\psi_j}{\beta_j}\right)-t_i\left(\frac{\eta\psi_i(b_i+\beta_i)-b_i\beta_i\psi_i}{b_i\beta_i^2}\right) \tag{A.11}$$

Damage by emissions

Damage experienced in country i is a function of emissions (e_j) in all countries, their transition rates (ψ_j) and spread of damage (ω_{ji}) determined by the type of pollution in conjunction with geographical position. We substitute earlier results into the emissions experienced by country i, to be substituted in turn later. Defining

$$\chi_p = \beta_p^{-1}(\alpha_p - 1) - \beta_p^{-1}\eta\left(\sum_j \frac{(\alpha_j - 1)b_j - (1 - a_j)\beta_j}{b_j\beta_j} - \bar{k_j}\right), \tag{A.12}$$

we can write

$$\sum_j \omega_{ji}e_j = \sum_j \omega_{ji}\psi_j k_j = \sum_j \omega_{ji}\psi_j\left(\chi_j + \frac{\eta}{\beta_j}\left(\sum_j \frac{t_j\psi_j}{\beta_j}\right) - \frac{t_j\psi_j}{\beta_j}\right)$$

$$= \left(\sum_j \omega_{ji}\psi_j\chi_j\right) + \left(\sum_j \frac{\eta\psi_j\omega_{ji}}{\beta_j}\left(\sum_j \frac{t_j\psi_j}{\beta_j}\right)\right) - \left(\sum_j \frac{t_j\omega_{ji}\psi_j^2}{\beta_j}\right). \tag{A.13}$$

Intermediary derivatives

To determine the reply functions, we will have to set the f.o.c. equal to zero. Here we derive the first derivatives needed to obtain the final results. The derivatives of interest (r), saving (s_i) and capital (k_i) w.r.t. a country i's own tax rate (t_i) are now easily determined.

$$\frac{\partial r}{\partial t_i} = -\eta\frac{\psi_i}{\beta_i} < 0, \qquad \frac{\partial r}{\partial t_j} = -\eta\frac{\psi_j}{\beta_j} < 0.. \tag{A.14}$$

$$\frac{\partial s_i}{\partial t_i} = b_i^{-1}\frac{\partial r}{\partial t_i} = -\eta\frac{\psi_i}{b_i\beta_i} < 0, \qquad \frac{\partial s_j}{\partial t_i} = b_j^{-1}\frac{\partial r}{\partial t_i} = -\eta\frac{\psi_i}{b_j\beta_i} < 0. \tag{A.15}$$

$$\frac{\partial k_i}{\partial t_i} = -\beta_i^{-1}\frac{\partial r}{\partial t_i} - \frac{\psi_i}{\beta_i} = \eta\frac{\psi_i}{\beta_i^2} - \frac{\psi_i}{\beta_i} < 0, \qquad \frac{\partial k_j}{\partial t_i} = -\beta_j^{-1}\frac{\partial r}{\partial t_i} = \eta\frac{\psi_i}{\beta_i\beta_j} > 0.. \tag{A.16}$$

Taking the first derivative of (negative) benefit from environmental damage of country p w.r.t. its tax rate t_p we get

$$D_{\sum\omega_{jp}e_j}\left(\sum\omega_{jp}e_j\right)\frac{\partial\sum\omega_{jp}e_j}{\partial t_p} = \delta_p\left(\sum\omega_{jp}e_j\right)\frac{\partial\sum_p\omega_{jp}e_j}{\partial t_i}$$

$$= \delta_p\left(\sum\omega_{jp}e_j\right)\frac{\partial\sum\omega_{jp}\psi_j k_j}{\partial t_i} = \delta_p\left(\sum\omega_{jp}e_j\right)\left(\sum_{j\neq i}\left(\omega_{jp}\psi_j\frac{\partial k_j}{\partial t_i}\right) + \omega_{ip}\psi_i\frac{\partial k_i}{\partial t_i}\right). \tag{A.17}$$

Substituting the first expression of Equation (A.16), we get

$$= \delta_p \left(\sum \omega_{jp} e_j\right) \left(\sum_{j \neq i} \left(\eta \frac{\omega_{jp}\psi_j\psi_i}{\beta_j\beta_i}\right) + \eta \frac{\omega_{ip}\psi_i^2}{\beta_i^2} - \frac{\omega_{ip}\psi_i^2}{\beta_i}\right). \tag{A.18}$$

We define $\kappa_{ip} = \delta_p \left(\eta \sum_j \left(\frac{\omega_{jp}\psi_j\psi_i}{\beta_j\beta_i}\right) - \frac{\omega_{ip}\psi_i^2}{\beta_i}\right)$ such that

$$\delta_p \left(\sum_j \omega_{jp} e_j\right) \frac{\partial \sum_j \omega_{jp} e_j}{\partial t_i} = \kappa_{ip} \sum_j \omega_{jp} e_j. \tag{A.19}$$

This term measures the marginal additional climate damage in country p when country i lowers its tax rate t_i. The term consists of the parameter δ_p, measuring country p's inherent sensitivity to the environmental change, and a term capturing the inflow of negative externalities due to the capital stock's new size and allocation.

Reply function BAU scenario

We present once more the welfare function of country i as in Equation (9):

$$W^i(t_1, ..., t_n) = U(\bar{k_i} - s_i) + X(k_i) + (1+r)(s_i - k_i) - D\left(\sum e_j\right)$$

Setting the first derivative of the welfare function w.r.t. t_i equal to zero and letting the subscript of the function represent the variable w.r.t. which the derivative is taken gives

$$W^i_{t_i} = -U_{s_i}(\bar{k_i} - s_i)\frac{\partial s_i}{\partial t_i} + X_{k_i}(k_i)\frac{\partial k_i}{\partial t_i} + \frac{\partial (1+r)(s_i - k_i)}{\partial t_i}$$

$$-D_{\sum \omega_{ji} e_j}\left(\sum \omega_{ji} e_j\right) \frac{\partial \sum \omega_{ji} e_j}{\partial t_i} = 0. \tag{A.20}$$

Using earlier results

$$W^i_{t_i} = -(1+r)\frac{\partial s_i}{\partial t_i} + (1 + r + t_i\psi_i)\frac{\partial k_i}{\partial t_i} + (s_i - k_i)\frac{\partial r}{\partial t_i} + (1+r)(\frac{\partial s_i}{\partial t_i} - \frac{\partial k_i}{\partial t_i})$$

$$-\delta_i \left(\sum \omega_{ji} e_j\right) \frac{\partial \sum \omega_{ji} e_j}{\partial t_i}$$

$$= t_i\psi_i \frac{\partial k_i}{\partial t_i} + (s_i - k_i)\frac{\partial r}{\partial t_i} - \kappa_i \sum_j \omega_{ji} e_j = 0. \tag{A.21}$$

Note that changes in utility from lower savings and lower capital use due to the time value of money (1+r) are offset by changes in the term of trade (s_i - k_i). Inserting the derivative of capital w.r.t. t_i yields

$$t_i\psi_i(\eta\frac{\psi_i}{\beta_i^2} - \frac{\psi_i}{\beta_i}) + (s_i - k_i)(-\frac{\eta\psi_i}{\beta_i}) - \kappa_i \sum_j \omega_{ji} e_j$$

$$= t_i \left(\frac{\psi_i^2 b_i \beta_i (\eta - \beta_i)}{b_i \beta_i^3} \right) - (s_i - k_i) \, (\frac{\eta \psi_i}{\beta_i}) - \kappa_i \sum_j \omega_{ji} e_j = 0. \tag{A.22}$$

Inserting the expression of Equation (A.11) for capital export gives

$$t_i \left(\frac{\psi_i^2 (\eta^2 (b_i + \beta_i) - b_i \beta_i^2)}{b_i \beta_i^3} \right) - (\frac{\psi_i \eta \zeta_i}{\beta_i})$$

$$+ \left(\frac{\eta^2 \psi_i (b_i + \beta_i)}{b_i \beta_i^2} \right) \left(\sum_{j \neq i} \frac{t_j \psi_j}{\beta_j} \right) - \kappa_i \left(\sum_j \omega_{ji} e_j \right) = 0. \tag{A.23}$$

Finally, inserting the expression of Equation (A.13) for the (negative) benefit from emissions yields

$$= - \left(\frac{t_i \psi_i^2}{\beta_i} \right) - (\frac{\psi_i \eta \zeta_i}{\beta_i}) + \left(\frac{\eta^2 \psi_i (b_i + \beta_i)}{b_i \beta_i^2} \right) \left(\sum_j \frac{t_j \psi_j}{\beta_j} \right)$$

$$-\kappa_{ip} \left(\sum_j \omega_{ij} \psi_j \chi_j \right) - \kappa_{ip} \left(\sum_j \frac{\eta \psi_j \omega_{ji}}{\beta_j} \left(\sum_j \frac{t_j \psi_j}{\beta_j} \right) \right) + \kappa_{ip} \left(\sum_j \frac{t_j \omega_{ji} \psi_j^2}{\beta_j} \right) = 0. \tag{A.24}$$

which can be rewritten to yield Equation (12).

Optimal tax rate full cooperation

The grand coalition's goal is to optimize joint welfare which can be expressed as

$$\sum_j W^j (t_1, ..., t_n) = \sum_j \left(U(\bar{k_j} - s_j) + X(k_j) + (1 + r)(s_j - k_j) - D \left(\sum e_j \right) \right). \tag{A.25}$$

Setting the first derivative of the joint tax vector equal to zero is equivalent to setting the first derivative of each separate element equal to zero. Therefore we set the first derivative w.r.t. t_i equal to zero and, using results from the BAU section, we write:

$$\left(\sum_j W^j \right)_{t_i} = \sum_j \left(t_j \psi_j \frac{\partial k_j}{\partial t_i} + (s_j - k_j) \frac{\partial r}{\partial t_i} - \delta_j \left(\sum \omega_{ij} e_j \right) \frac{\partial \sum \omega_{ij} e_j}{\partial t_i} \right) = 0. \tag{A.26}$$

We substitute expressions from Equations (A.14), (A.16) and (A.19) such the f.o.c. reads

$$\left(\sum_j t_j \left(\frac{\eta \psi_i \psi_j}{\beta_i \beta_j} \right) \right) + t_i \left(\frac{\psi_i^2}{\beta_i} \right) - \sum_j \left(\frac{\eta \psi_i}{\beta_i} \left(\zeta_j - \left(\frac{\eta (b_j + \beta_j)}{b_j \beta_j} \right) \left(\sum_j \frac{t_j \psi_j}{\beta_j} \right) + \frac{t_j \psi_j}{\beta_j} \right) \right)$$

$$- \sum_j \kappa_j \left(\sum \omega_{ij} e_j \right)$$

$$= \frac{\eta\psi_i}{\beta_i}\left(\sum_j \frac{t_j\psi_j}{\beta_j}\right)+t_i\left(\frac{\psi_i^2}{\beta_i}\right)-\left(\frac{\eta\psi_i\sum_j\zeta_j}{\beta_i}\right)+\frac{\eta^2\psi_i}{\beta_i}\sum_j\left(\frac{b_j+\beta_j}{b_j\beta_j}\right)\left(\sum_j\frac{t_j\psi_j}{\beta_j}\right)$$

$$\frac{\eta\psi_i}{\beta_i}\left(\sum_j\frac{t_j\psi_j}{\beta_j}\right)-\sum_j\kappa_j\left(\sum\omega_{ij}e_j\right)=0. \tag{A.27}$$

Note that $\sum_j\left(\frac{b_j+\beta_j}{b_j\beta_j}\right)=\eta^{-1}$, such that

$$t_i\left(\frac{\psi_i^2}{\beta_i}\right)-\left(\frac{\eta\psi_i\sum_j\zeta_j}{\beta_i}\right)+\frac{\eta\psi_i}{\beta_i}\left(\sum_j\frac{t_j\psi_j}{\beta_j}\right)-\sum_j\kappa_j\left(\sum\omega_{ij}e_j\right)=0. \tag{A.28}$$

Inserting Equation (13) yields

$$t_i\left(\frac{\psi_i^2}{\beta_i}\right)-\left(\frac{\eta\psi_i\sum_j\zeta_j}{\beta_i}\right)+\frac{\eta\psi_i}{\beta_i}\left(\sum_j\frac{t_j\psi_j}{\beta_j}\right)-\sum_j\kappa_{ij}\left(\sum_j\omega_{ij}\psi_j\chi_j\right)$$

$$-\sum_j\kappa_{ij}\left(\sum_j\frac{\eta\omega_{ij}\psi_j}{\beta_j}\sum_j\frac{t_j\psi_j}{\beta_j}\right)+\sum_j\kappa_{ij}\left(\sum_p\frac{t_j\omega_{pj}\psi_j^2}{\beta_j}\right)=0 \tag{A.29}$$

which can be rewritten to yield Equation (15).

Reply function climate coalitions

A coalition's goal is to optimize the coalition's joint welfare which can be expressed as

$$\sum_{p\in C}W^p(t_1,...,t_n)=\sum_{p\in C}\left(U(\bar{k_p}-s_p)+X(k_p)+(1+r)(s_p-k_p)-D\left(\sum_j\omega_{jp}e_j\right)\right) \tag{A.30}$$

for every country $i\in C$ with coalition partners $p\in$ C. Once more, setting the first derivative of the joint tax vector equal to zero is equivalent to setting the first derivative of each separate element equal to zero. Therefore we set the first derivative w.r.t. t_i equal to zero and, using results from the BAU section, we write: The first order condition becomes

$$\left(\sum_p W^{p\in C}\right)_{t_i}=\sum_{p\in C}\left(t_p\psi_p\frac{\partial k_p}{\partial t_i}+(s_p-k_p)\frac{\partial r}{\partial t_i}-\delta_p\left(\sum_j\omega_{jp}e_j\right)\frac{\partial\sum_j\omega_{jp}e_j}{\partial t_i}\right)=0 \tag{A.31}$$

We substitute expressions from Equations (A.14), (A.16) and (A.19) such the f.o.c. reads

$$\left(\sum_{p\in C}t_p\left(\frac{\eta\psi_i\psi_p}{\beta_i\beta_p}\right)\right)-\left(\frac{t_i\psi_i^2}{\beta_i}\right)-\frac{\eta\psi_i}{\beta_i}\sum_{p\in C}\left(\zeta_p-\eta\left(\frac{b_p+\beta_p}{b_p\beta_p}\right)\left(\sum_j\frac{t_j\psi_j}{\beta_j}\right)+\frac{t_p\psi_p}{\beta_p}\right)$$

$$-\sum_{p\in C}\kappa_{ip}\left(\sum_{j}\omega_{jp}e_j\right)$$

$$=\frac{\eta\psi_i}{\beta_i}\left(\sum_{p\in C}\frac{t_p\psi_p}{\beta_p}\right)-\left(\frac{t_i\psi_i^2}{\beta_i}\right)-\frac{\eta\psi_i}{\beta_i}\sum_{p\in C}\zeta_p+\frac{\eta^2\psi_i}{\beta_i}\sum_{p\in C}\left(\frac{b_p+\beta_p}{b_p\beta_p}\right)\left(\sum_j\frac{t_j\psi_j}{\beta_j}\right)$$

$$-\frac{\eta\psi_i}{\beta_i}\left(\sum_{p\in C}\frac{t_p\psi_p}{\beta_p}\right)-\sum_{p\in C}\kappa_{ip}\left(\sum\omega_{jp}e_j\right)=0. \tag{A.32}$$

Once more, note that $\sum_j\left(\frac{b_j+\beta_j}{b_j\beta_j}\right)=\eta^{-1}$, such that

$$\frac{\eta^2\psi_i}{\beta_i}\sum_{p\in C}\left(\frac{b_p+\beta_p}{b_p\beta_p}\right)\left(\sum_j\frac{t_j\psi_j}{\beta_j}\right)-\left(\frac{t_i\psi_i^2}{\beta_i}\right)-\frac{\eta\psi_i}{\beta_i}\sum_{p\in C}\zeta_p-\sum_{p\in C}\kappa_{ip}\left(\sum\omega_{jp}e_j\right)=0. \tag{A.33}$$

Inserting Equation (13) yields

$$\frac{\eta^2\psi_i}{\beta_i}\sum_{p\in C}\left(\frac{b_p+\beta_p}{b_p\beta_p}\right)\left(\sum_j\frac{t_j\psi_j}{\beta_j}\right)-\left(\frac{t_i\psi_i^2}{\beta_i}\right)-\frac{\eta\psi_i}{\beta_i}\sum_{p\in C}\zeta_p-\sum_{p\in C}\kappa_{ip}\left(\sum_j\omega_{jp}\psi_j\chi_j\right)$$

$$-\sum_{p\in C}\kappa_{ip}\left(\sum_j\frac{\eta\psi_j\omega_{jp}}{\beta_j}\left(\sum_j\frac{t_j\psi_j}{\beta_j}\right)\right)+\sum_{p\in C}\kappa_{ip}\left(\sum_j\frac{t_j\omega_{jp}\psi_j^2}{\beta_j}\right)=0.$$

Which can be rewritten to yield Equation (16).