Research cooperation and international standards in a model of coalition stability[☆]

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Abstract

Suggestions on international cooperation in climate policy beyond 2012 include substituting or complementing international environmental agreements (IEA) with technology oriented agreements (TOA). We look at the impact of TOA on environmental cooperation in a framework of coalition stability. Using a numerical model, we analyze the differences of several TOA and how they interact. We find that participation in and environmental effectiveness of the IEA are raised less effectively when the TOA focuses on research cooperation in mitigation technology rather than cooperation on augmenting productivity in the private good sector. This is due to the former having an effect on all actors via emissions, whereas effects of the latter are exclusive to research partners. For the same reason, we find that restricting research cooperation to the coalition is only credible when it focuses on productivity. Technology standards that reduce the emission intensity of production are unlikely to raise participation by themselves and may suffer from inefficiencies. However, these disadvantages do not apply when standards are implemented as a complementary instrument. Separately negotiated technology standards may hence facilitate participation in an IEA without adding to its complexity.

Keywords: Coalition Formation, International Environmental Agreements, Issue Linking, Non-cooperative Game Theory, R&D Spillovers, Technology Standards

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1. Introduction

Achieving full cooperation in a self-enforcing international environmental agreement (IEA) is difficult when the underlying game presents the actors with the following dilemma: while global cooperation is socially optimal, it is often better for a number of players to act as free-riders, i.e. enjoying the benefits of other players' abatement efforts without reducing their own emissions. Consequently, it is a standard result in non-cooperative game theoretic models that voluntary participation in environmental cooperation alone tends to be low (see for example Carraro and Siniscalco, 1992, and Barrett, 1994, or the more recent Finus et al., 2006).

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By introducing additional incentives, the structure of the game may be changed making cooperation easier to achieve. Barrett and Stavins (2003) categorize these incentives into three groups: First, positive incentives which aim to encourage participation by means of side payments, permit allocation, and issue linking. Second, negative incentives such as reciprocal measures, financial penalties, and trade restrictions, which attempt to deter free-riding by threatening some sort of punishment. Third, Barrett and Stavins name treaty mechanisms as a means to set strategic incentives. Examples are the proposal by Schelling (1998) for countries to pledge emission reductions on a voluntary and unenforced basis, and the standards setting approach suggested by Barrett (2003). In this paper, we focus on issue linking, specifically linking environmental cooperation to technology oriented agreements (TOA). In particular, we explore TOA that implement research cooperation associated with technology spillovers, and international technology standards reducing the emission intensity of production. We distinguish two alternative areas of research cooperation: research on mitigation technology and research augmenting the productivity of the technology in the private good sector. The analysis is carried out using a numerical model with nine symmetric regions. The following sections introduce the key concepts – issue linking, spillovers, technology standards, and coalition formation – along the relevant literature.

1.1. Issue Linking

The unfavorable incentive structure in climate change mitigation is due to the public good character of a stable climate. Enjoying a stable climate is non-rival, and there are no means of excluding anybody from doing so, hence the possibility to free-ride.

Issue linking attempts to improve the incentive structure by linking the provision of the public good to an exclusive access to a club good (Carraro, 1999). When the attractiveness of the club good outweighs the incentive to free-ride, the dilemma is overcome. Possible candidates for such club goods are technology oriented agreements. De Coninck et al. (2007) provide an overview of TOA stressing the potential role of TOA in addressing the free-riding incentives in climate protection negotiations.

In particular agreements on cooperation on R&D, which foster technology spillovers among research partners, have these qualities of a club good (non-rivalry and excludability). Previous issue linking modeling studies have analyzed the potential of spillovers to raise participation in international cooperation. Here, the key assumption is that research partners are privy to spillovers that do not extend to others. We will adopt this assumption in our modeling (see Section 2.2). In these studies, cooperative research and development creates spillovers concerning production costs (Carraro and Siniscalco, 1997; Botteon and Carraro, 1998), profit (Katsoulacos, 1997), energy efficiency (Kemfert, 2004), productivity and emission intensity simultaneously (Buchner and Carraro, 2006), and marginal abatement costs (Nagashima and Dellink, 2008).

1.2. Potential of spillovers

Research and development is known to have spillovers. Griliches (1992), for example, reviews a number of empirical studies which estimate social and private rates of return to R&D. Griliches concludes, “R&D spillovers are present, their magnitude may be quite large, and social rates of return remain significantly above private rates.”

Research partnerships may facilitate these spillovers. There are numerous reasons for cooperative research, ranging from costs minimization to strategic considerations. In particular, the list of reasons includes internalizing spillovers, e.g. learning from partners, transfer of technology and technical knowledge, and increasing efficiency and synergies through network, as well as exploiting the non-rivalry of knowledge, e.g. by sharing R&D costs (Hagedoorn et al., 2000). Of course, raising the spillover intensity is not a policy instrument at the disposal of governments. But by encouraging research partnerships spillovers might be fostered indirectly.

Existing governmental policies aimed at encouraging cooperative R&D focus on providing legal frameworks as well as financial support, noteworthy the EU Framework Programmes on Research and Technological Development (FWP). Aimed at industry as well as universities and research laboratories, the FWP offer financial support of up to 50 percent of the total joint research costs but require the research partnership to include members from at least two EU countries (Hagedoorn et al., 2000), i.e. the FWP are a prime example of boosting international research cooperation.

1.3. Potential of international standards

Setting international technology standards has been suggested as a substitute as well as a complement to international climate agreements, for example by requiring all new electricity power plants to be equipped with carbon capture and storage (Edmonds and Wise, 1999). More generally, Scott Barrett's *technology centered approach* combines technological R&D with international technology standards (Barrett, 2003, Ch. 15). Barrett argues that technology standards are attractive because a broad adoption of technology standards is more likely than a broad participation in a Kyoto-style climate agreement due to the particular strategic incentives. Indeed, the literature on technology standards lists a number of reasons that would spur the adoption of such standards (see for example Farrell and Saloner, 1987; David and Greenstein, 1990; Barrett, 2003). Among these reasons are: first, network externalities, i.e. the higher the number of adopters, the larger the benefits for additional adopters. This positive feedback makes a broad adoption likely once a threshold 'minimum participation' has been reached. Second, when a broad adoption is anticipated, fear of lock-in in non-compliant technologies will further encourage adoption. Third, standards help to reduce costs when economies of scale can be exploited.

Whether these incentives suffice to provide effective environmental protection has been challenged (Philibert, 2004; de Coninck et al., 2007), questioning whether the favorable incentives cited by Barrett would indeed arise in case of technology standards aimed at reducing carbon emissions. Resolving these differences is beyond the scope of this paper, where we will focus on the effect of widely implemented technology standards on international cooperation. Thus for our analysis we will adopt Barrett's point of view assuming that a wide adoption of technology standards was fostered by the underlying incentive structure, i.e. we will assume that international technology standards have been adopted globally due to reasons that are exogenous to the model.

When technology standards are set as part of climate change mitigation policies, their aim is to reduce greenhouse gas emissions. This can be achieved by implementing a broad set of technology standards covering a wide range of the sectors causing GHG emission. For examples, there is a large potential to reduce emissions from the Chinese transport sector, the residential sector, and the iron and steel sector by implementing fuel economy standards for automobiles, promoting energy-efficiency standards for household electrical appliances, and using the best available technologies for iron and steel production, respectively (Sugiyama et al., 2006). Naturally, such technology standards would reduce the emission intensity of the Chinese economy, given that the produced goods and services are not substituted through other non-standardized sectors. However, assuming an economy-wide application of standards and a general complementarity of sector outputs the above assertion certainly holds. The adoption of standards on the technology level and the emission intensity of the economy are therefore closely linked. We will make use of this when we model the macro-economic effects of technology standards, namely their impact on emission intensity rather than actual standards on the technology level.

1.4. Coalition formation

The formal analysis of self-enforcing international environmental agreements in non-cooperative game theory was pioneered by Barrett (1991a,b) and Carraro and Siniscalco (1992, 1993), and has recently been surveyed by Finus (2008). The incentive of issue linking, which is the focus of this paper, has been studied using both, conceptual and empirically calibrated models.

The first conceptual study of issue linking in a climate change related context was Carraro and Siniscalco (1995), extended in Carraro and Siniscalco (1997), who investigate linkage of environmental cooperation to cooperation on R&D in a static three-stage game showing that linkage indeed furthers participation. Spillovers are introduced between nation states or regions which are also the only entities taking decisions. Most of the calibrated numerical models discussed below follow this setting. They generally do not consider who controls spillovers, and what the consequences are when spillovers are not or only partly internalized. Katsoulacos (1997) and Golombek and Hoel (2008) consider these points in analytical models albeit abstracting from coalition formation.

In particular, Katsoulacos (1997) questions the approach of having one entity decide upon both, environmental and technological cooperation, arguing that the decision to cooperate on technological R&D is taken by firms, not governments. Consequently, his model distinguishes firms deciding on spillover levels and governments deciding on R&D subsidies aimed at encouraging spillovers. The analysis is restricted to two countries, which can be shown to enter joint cooperation on R&D and environment if the gains from subsidies are large enough.

In Golombek and Hoel (2008), emission policy is modeled by assuming an international agreement that specifies country specific optimum emission quotas but does so ignoring the spillover externality. The resulting second-best quotas are more stringent than is first-best. The surprising result is that allowing international permit trade in this second-best situation will be welfare decreasing: the more stringent permit allocations induce some of the lacking R&D investments in a country specific way. Permit trade interferes with this incentive. This analysis is extended in Golombek and Hoel (2009), which explores the consequences of setting a technology policy (modeled as an R&D subsidy) as well as a mitigation policy (modeled by assuming an international agreements that establishes a carbon tax). They show that if the carbon tax is not at its socially optimal (Pigouvian) level then the second-best R&D subsidy may exceed its first-best level.

The stylized models discussed above agree that issue linking with spillovers has positive effects on participation in the IEA. It is beyond the scope of these models to assess the extent of spillovers necessary to induce high levels of participation. A number of numerical models calibrated to empirical data have been applied to the issue. In principle, these models ought to allow a quantification of spillover effects. But in these models, the extent of the positive effect on participation varies, ranging from complete success in stabilizing full cooperation (Botteon and Carraro, 1998; Kemfert, 2004), to merely marginal increases of the coalition size (Nagashima and Dellink, 2008). These models differ in a great number of ways and it is unclear which modeling assumptions give rise to these differences in model results.

The analysis in Botteon and Carraro (1998) extends the earlier work by Carraro and Siniscalco (1997) by adding heterogeneity based on empirical data to this model. While this renders the model analytically intractable, they confirm their earlier findings numerically: participation in the IEA rises with spillover intensity including full cooperation of five out of five players.

Kemfert (2004) uses a yet broader data basis: the article by Kemfert explores the effects of issue linking in a CGE model calibrated to the GTAP database (McDougall et al., 1998). The scenarios include cooperation on energy efficiency R&D as well as trade barriers against non-cooperating countries. In this model, introducing R&D cooperation has a strong effect on the incentive to participate in an IEA. With R&D cooperation, all four of the negotiating countries want to join the IEA, compared to none in the base case, i.e. full cooperation is internally stable.[1]

Nagashima and Dellink (2008) use the STACO model to explore the effects of technology spillovers on the stability of coalitions. They focus on spillovers in mitigation technology, and model these through changes of the marginal abatement cost curve. They observe that spillovers have a positive effect on the abatement effort, but the number of participating regions is only increased by one beyond the default maximum participation of six out of twelve regions. This finding proves robust against a variation of the intensity of spillovers and the way spillovers affect the marginal abatement costs curves, as well as the choice of the indicator for the state of technology. Thus, the authors conclude that technology spillovers do not substantially increase the success of IEA.

The positive effect of R&D cooperation on participation is also confirmed by Buchner et al. (2005) who apply a multi-actor optimal growth model to questions of issue linkage. However, the authors limit their analysis to a selected set of coalitions, in particular the coalition of Kyoto signatories plus the United States, to explore the effect of linking on the incentives for the United States in particular. There is therefore no assessment of higher or maximum participation levels. They note, however, that making R&D cooperation dependant on environmental cooperation is not credible, i.e. Kyoto signatories prefer to cooperate on R&D with the United States even if the latter act non-cooperatively on emission abatement.

Most authors acknowledge that the intensity of spillovers is an important determinant, but given the state of the literature, it is difficult to provide a sound empirical basis for the choice of spillover intensity. Variation of this key parameter, as studied in Botteon and Carraro (1998) and Nagashima and Dellink (2008), reveals the sensitivity of this key assumption, yet the selected values for spillover intensity cannot be compared across models. Furthermore, the sources of spillovers differ between models. The implication of the kind of spillover, e.g. whether related to productivity as in Botteon and Carraro (1998), or related to mitigation technology as in Nagashima and Dellink (2008) has not been studied.

1.5. Novelty

We go beyond existing studies by comparing spillovers that arise from two different research sectors, augmenting either productivity in producing the private good or mitigation technology, and show that the effectiveness of spillovers depends on the type of knowledge that spills over. The reason is that, unlike in the case of productivity R&D, progress in mitigation technology has an external effect via its impact on emissions, making it easier to achieve high levels of cooperation by linking to productivity R&D. These results on participation carry over to similar conclusions about the impact of IEA on environmental effectiveness and global welfare. In order to increase the comparability of spillover intensity, we estimate the gains from spillovers in terms of additional consumption.

Furthermore, the effect of spillover from cooperative R&D has so far only been investigated in isolation from international technology standards. We complement spillovers by technology standards and explore the interdependence of the two, as well as the scope of technology

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[1] Coalitions are internally stable when no member has an incentive to leave. We define this formally below.

standards to stabilize coalitions by themselves. We find that cooperative R&D and technology standards are mutually reinforcing in their positive effect on international cooperation. By themselves, technology standards have almost no effect on participation in the IEA. The remainder of this paper follows the usual three steps definition of the model (Section 2), results (Section 3) including some sensitivity analysis (Section 4), and conclusions (Section 5).

2. The Model

We approach the assessment of coalition stability, research cooperation, and international standards in a multi-actor optimal growth model, which is a common modeling framework for the economy-climate stock pollutant problem in general (e.g. Nordhaus and Yang, 1996; Kypreos and Bahn, 2003; Bosetti et al., 2006) and also in coalition stability analyses (e.g. Eyckmans and Tulkens, 2003; Buchner and Carraro, 2006). In particular, it is appropriate for the long economic time horizon required for an integrated assessment of global warming (Edenhofer et al., 2006). Furthermore, intertemporal utility maximization of a representative agent gives macroeconomic models a firm micro-foundation and makes them suitable for welfare analysis (Turnovsky, 2000, pp. 3).

2.1. Model Equations

Preferences

Within this framework, each region i is modeled following Ramsey (1928) as a maximizer of its intertemporal welfare W_i. Here, we chose the utilitarian welfare function with an instantaneous utility function U, $U' > 0$ and $U'' < 0$, and per capita consumption c_{it}/l_{it} as an indicator of well-being. Parameter ρ denotes the pure rate of time preference, $-\eta$ is the elasticity of marginal utility, and l_{it} the size of the population.

$$W_i = \int_0^\infty l_{it}\, U(c_{it}/l_{it})\, e^{-\rho t}\, \mathrm{dt} \tag{1}$$

$$U(c_{it}/l_{it}) = \begin{cases} \dfrac{(c_{it}/l_{it})^{1-\eta}}{1-\eta} & \text{if } \eta \neq 1 \\ \log(c_{it}/l_{it}) & \text{if } \eta = 1 \end{cases} \tag{2}$$

Technology

Each region produces a single good using Cobb-Douglas technology F from capital k_{it} and exogenously given labor supply l_{it}, which is subject to labor enhancing technological change $\tilde{a}_{it}$. Parameter β is the income share of capital.

$$F(\tilde{a}_{it} l_{it}, k_{it}) = (\tilde{a}_{it} l_{it})^{1-\beta} k_{it}^{\beta} \tag{3}$$

Capital is made up from past investments, in_{it}. New ideas that contribute to labor productivity a_{it} in country i are a function of the funds invested in R&D, ia_{it}. Parameters $\lambda \leq 1$ and $\Phi \geq 0$ describe effects of researchers "stepping on tows" and "standing on shoulders," respectively. Parameter ξ_a is a scaling parameter. This knowledge production function is proposed in an empirical study by Jones and Williams (1998) and has been applied in integrated assessment in Edenhofer et al. (2005, 2006).

$$\frac{d}{dt}k_{it} = in_{it} \tag{4}$$

$$\frac{d}{dt}a_{it} = \xi_a \left(ia_{it}\right)^{\lambda} \left(a_{it}\right)^{\Phi} \tag{5}$$

Labor productivity $\tilde{a}_{it}$ encompasses the accumulated knowledge of region i (a_{it}) as well as eventual spillovers from other regions. In the base case we assume no spillovers between regions and simply set $\tilde{a}_{it} = a_{it}$. When R&D spillovers are modeled, we use a weighted aggregate of labor productivity in all regions. This approach is also used in the empirical literature on R&D spillovers, for example in Griliches (1992).

$$\tilde{a}_{it} = \sum_j \varepsilon^a_{ij} a_{jt} \tag{6}$$

Griliches (1992) interprets ε^a_{ij} as the "economic and technological distance" between i and j where large values of ε^a_{ij} indicate "closeness". We always set $\varepsilon^a_{ii} = 1$, and in the base case $\varepsilon^a_{ij} = 0$ for $i \neq j$. Values of $\varepsilon^a_{ij} > 0$ indicate spillovers and are discussed below.

Climate Dynamics

We model greenhouse gas emissions e_{it} as a by-product of economic activity (y_{it} below in Equation 15). Emission intensity of production decreases exogenously at an annual rate of ν but may be additionally decreased by investing in a mitigation stock km_{it}. Mitigation km_{it} reduces emission intensity σ_{it} with diminishing effectiveness described by $\gamma < 1$.

$$e_{it} = \sigma_{it} \exp(-\nu t)\, y_{it} \tag{7}$$

$$\sigma_{it} = (1 + \tilde{km}_{it})^{-\gamma} \tag{8}$$

$$\frac{d}{dt}km_{it} = \xi_m im_{it} \tag{9}$$

Parameter ξ_m determines the effectiveness of investments im_{it}. As before in the case of productivity, we allow for spillovers but set the spillover intensity ε^m_{ij} to $\varepsilon^m_{ij} = 0$ ($i \neq j$) in the base case and $\varepsilon^m_{ii} = 1$.

$$\tilde{km}_{it} = \sum_j \varepsilon^m_{ij} km_{jt} \tag{10}$$

To account for the stock pollutant character of global warming, we include a stylized model of the climate system (Petschel-Held et al., 1999). Parameters of the climate system are defined in Appendix Appendix A. The total stock of atmospheric greenhouse gases ce_t grows due to the instantaneous emissions of all countries

$$\frac{d}{dt}ce_t = \sum_j e_{jt} \tag{11}$$

and is linked to the greenhouse gas concentration $conc_t$ according to

$$\frac{d}{dt}conc_t = B\,ce_t + \beta^P \sum_j e_{jt} - \sigma^P(conc_t - conc_0) \tag{12}$$

The concentration, in turn, determines the change of global mean temperature $temp_t$ by

$$\frac{d}{dt}temp_t = \mu \log(conc_t/conc_0) - \alpha^P(temp_t - temp_0) \tag{13}$$

For a detailed description of the climate equations and their parameters we refer to the original publication.

Adapted from Nordhaus and Yang (1996), temperature changes cause climate change damages, destroying a fraction $1 - \Omega_{it}$ of economic output:

$$\Omega_{it} = 1/(1 + dam1_i(temp_t)^{dam2_i}) \tag{14}$$

$$y_{it} = \Omega_{it}F(k_{it}, l_{it}) \tag{15}$$

The physical budget constraint closes the economy.

$$y_{it} = c_{it} + in_{it} + ia_{it} + im_{it} \tag{16}$$

2.2. Coalition Formation

Coalition formation is modeled as a two stage game. In the first stage, a membership game is played, i.e. regions choose whether to become members and henceforth act cooperatively on emission abatement with the other coalition members, or to remain individual entities as non-members acting non-cooperatively (Partial Agreement Nash Equilibrium, see Chander and Tulkens, 1995). In the second stage, the emission game, non-members and the coalition (acting as one player) determine their emissions indirectly by deciding on their consumption and investment behavior.

Coalition Stability

Among all possible coalitions in a set of players N, we consider *stable* coalitions in the sense of *internal* and *external stability* of d'Aspremont and Gabszewicz (1986). A coalitions $S \subseteq N$ is internally stable if no member has an incentive to leave the coalition, and it is externally stable if no non-member has an incentive to join. The coalition is thus self-enforced by economic incentives.

R&D Cooperation and Issue Linking

When applied to the provision of a public good, the motivation for issue linking is to offset the incentive to free-ride on the non-excludable benefits of the public good by the incentive to gain access to an (excludable) club good (Perez, 2005). We adopt this view for our paper by identifying the coalition of regions dedicated to cooperation on emission reduction with a club of regions that shares spillovers from R&D.

Spillovers become a *club good* of the coalition S via the spillover intensities ε_{ij} in Equation 6 or Equation 10, which compute the weighted sums of productivity and mitigation, respectively. We set only spillover intensities ε_{ij} for $i, j \in S$ to non-zero levels.[2] This restricts spillovers to coalition members. In contrast, if spillovers of cooperative R&D within the coalition are a *public good*, spillovers extend to all regions, in which case we can set ε_{ij} for $i \in S$, $j \in N$ and $i \neq j$ to positive values. We use the public good case when we test credibility of the club good assumption.

International Standards

As argued in the introduction, standards on the technology level exhibit incentives that foster a broad adoption of such standards on their own right. In this study, we are interested in the effects of an existing standard on participation and issue linking. Therefore, we assume that the decision of adopting the standards has already taken place, i.e. this decision is exogenous to our model and applies to all players.[3]

We model the effect of international technology standards by requiring a reduction of emission intensity σ_{it} by a fraction θ of the non-cooperative equilibrium intensity σ_{it}^{NC}.

$$\sigma_{it} \quad \leq \quad (1-\theta)\,\sigma_{it}^{NC} \tag{17}$$

Formally, this is the same as a performance standard (e.g. Montero, 2002, p28).[4] However, as argued in the introduction, setting technology standards aiming for climate change mitigation is closely linked to reducing the emission intensity. We therefore model existing technology standards by describing their effect on the macro-economic emission intensity. The implicit assumption is that a broad adoption of technological standards aimed at low emissions technologies will translate into lower emission intensity on the macro-economic level. While this is plausible, it is clearly desirable to check this assumption in a model with the necessary technological detail in the future.

2.3. Solving the Model

A solution to the two staged game of, first, membership, and second, emissions, is solved numerically by backward induction. In our case this means solving all possible Partial Agreement Nash Equilibria (Chander and Tulkens, 1995), where the behavior of the coalition is determined in a joint maximization of welfare for all members, and non-members act selfishly, i.e. they maximize individual welfare.

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[2] This formulation of spillovers does not require the recipients to build up any absorptive capacity (for example Kneller, 2005). However, in the context of symmetric players we can presume mutual R&D investments by all regions that benefit from spillovers.

[3] Adoption of the international standards may be viewed as a third stage game of the coalition formation game taking place before the membership game: Players meet to decide on the adoption of standards first, then, based on the (possibly partial) standards agreement, go on to decide upon membership in the environmental agreement, and finally decide upon emission strategies. In this setting, our assumption is that the outcome of the first stage is adoption of standards by all players. This is also a welcome reduction of the computational burden (i.e. we only explore two out of nine possible outcomes of the first stage: full adoption and no adoption at all).

[4] The literature distinguishes technology standards (or equipment standards) from performance standard. The positive effects of technology standards are often due to the ability of these standards to enforce compatibility. Performance standards are technology-neutral. This characteristic is likely to increase their cost-effectiveness when applied to emission reduction but they lack much of the positive incentives of equipment standards (Barrett, 2003, Ch. 9).

The Nash Equilibrium of non-members and the coalition (acting as one player) is computed by a fixed point iteration of $s = G(s)$, where $s = (s_i)$ is the vector of strategies and G is the mapping of the players best responses. Strategies s_i consist of time paths for emissions e_{it}, and investments in productivity a_{it} and mitigation km_{it}. We compute G by numerically solving the following non-linear problems using GAMS/CONOPT (Brooke et al., 1988; Drud, 1994):

$$\begin{aligned}
\forall_{i\in S} \quad & \max \sum_{i\in S} W_i \\
& \text{subject to equations (1) to (16)} \\
& \text{and } e_{jt} = \overline{e_{jt}}, km_{jt} = \overline{km}_{jt}, a_{jt} = \overline{a_{jt}} \text{ for } j \notin S \\
\forall_{i\notin S} \quad & \max W_i \\
& \text{subject to equations (1) to (16)} \\
& \text{and } e_{jt} = \overline{e_{jt}}, km_{jt} = \overline{km}_{jt}, a_{jt} = \overline{a_{jt}} \text{ for } j \neq i
\end{aligned}$$

The notation $s = \bar{s}$ designates that these variable are kept fixed at their previous levels (or, in the first iteration, their initial values). This is the very definition of the Nash Equilibrium where agents are maximizers, *given the behavior of all other agents*. The fixed values are updated in-between steps of the iteration. We approximate the infinite time horizon by running the model for an equivalent of 250 years in 5 year steps. In terms of dynamic game theory, this algorithm computes an open-loop Nash Equilibrium.

The Nash Equilibrium determines the payoff matrix of the second stage, the emission game. The first stage, the membership game, is solved by checking the conditions of stability for all possible coalitions, i.e. we test any given coalition S for internal stability:

$$W_i|_S \geq W_i|_{S\setminus\{i\}} \text{ for } i \in S$$

and external stability:

$$W_j\big|_S > W_j\big|_{S\cup\{j\}} \text{ for } j \notin S$$

3. Results

For our analyzes, we run the following experiments: To assess the impact of spillover intensity and the stringency of standards on stable coalition size, environmental effectiveness, and welfare, we systematically vary θ as well as ε^a_{ij} and ε^m_{ij} for $i, j \in S$, with the coalition S ranging from the empty set to the set of all players (see Equations 6, 10, and 17). For exploring the credibility of threatening exclusive access to spillovers we additionally need to vary ε^a_{ij} and ε^m_{ij} for $i \in S$ and $j \in N$.

3.1. Participation in Environmental Cooperation

The first experiment looks at the effect of spillovers on coalition formation. We plot the size of the largest stable coalition (participation) for different spillover intensities.

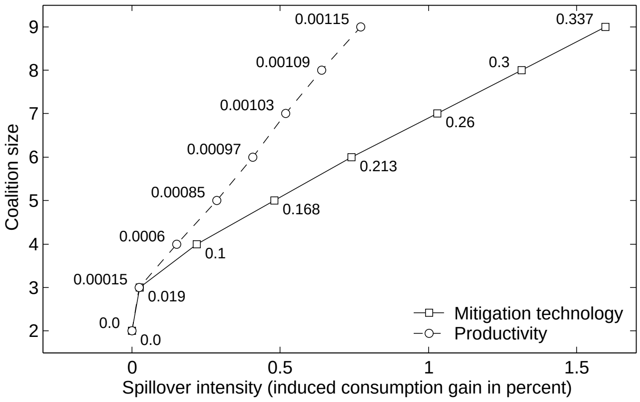

Figure 1: Participation (size of the largest stable coalition) as a function of spillover intensity. Spillover intensity is measured as *induced consumption gain*, i.e. the increase due to spillovers in discounted consumption for the respective coalition size, relative to the no-spillovers case (see main text). The values of spillover intensity parameters ε^m and ε^a are given next to the data points.

Cooperative R&D

To make spillovers of knowledge in mitigation technology and productivity comparable, we use *induced consumption gains* on the x-axis. Spillovers are manna from heaven compared to an economy without spillovers, and the additional payoff due to the same parameter value of the spillover intensity of productivity, ε^a, or mitigation technology, ε^m, may vary. The induced consumption gain is the additional consumption due to spillovers for the coalition under consideration and thus a proxy for its intensity. Technically, we take the difference of consumption paths with and without spillovers, discounted using a 3 percent discount rate. We convert to percentages of discounted base case consumption. We prefer a consumption based metric to a welfare metric to make the order of magnitude of the necessary spillovers easier to grasp.

In Figure 1 we observe the following: First, participation is low in absence of spillovers. This is in line with the literature and confirms that players in this model are indeed facing a dilemma, i.e. the incentive to free-ride is large enough for players to act non-cooperatively. Second, for both kinds of spillovers participation rises with spillover intensity. Again, this is in line with the literature. For high spillovers, full cooperation is supported. Third, participation rises more rapidly in the case of productivity cooperation. This is the case in terms of parameter values, which are smaller by a couple of orders of magnitude, as well as, more importantly, in terms of induced consumption gains.

To understand why productivity R&D is more effective in raising participation, we take a closer look at how spillovers raise participation, i.e. create incentives for larger stable coalitions. In particular, we take a look at payoffs received inside and outside a given coalition, i.e. the *inside payoff* of a player within the coalition of size n versus the *outside payoff* of the same player should she abandon the coalition and instead face the remaining coalition of $n-1$ players as a non-member.

The left graph in Figure 2 shows payoffs for introducing spillovers in productivity, the right hand graph shows results of introducing spillovers in mitigation technology. Both figures show

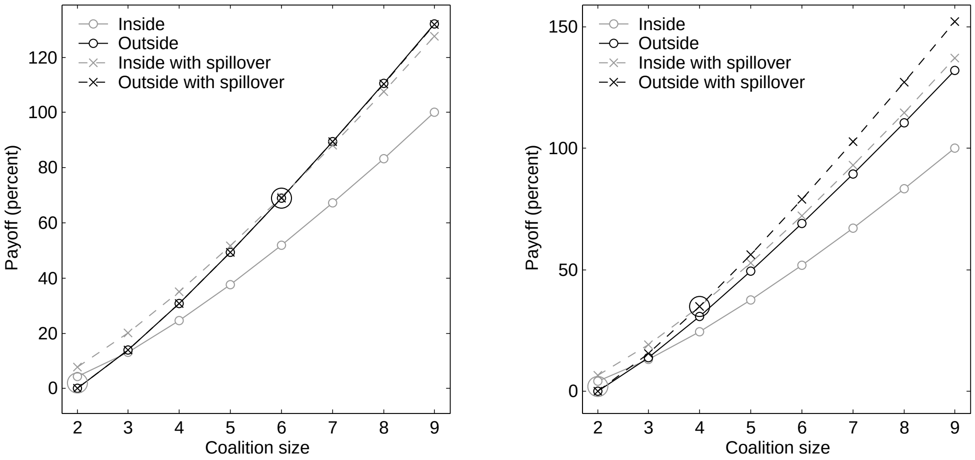

Figure 2: Payoff inside and outside of a given coalition. The figures compare the *inside payoff* received by a member of a coalition of size n (on the x-axis) with the *outside payoff* of a non-member free-riding on the effort of a coalition of size $n-1$. An inside payoff larger than an outside payoff indicates a stable coalition. We show payoffs for the base case without spillovers, and one exemplary case with spillovers, for productivity (left) and mitigation spillovers (right). The corresponding data points for stable coalitions are circled. Payoffs are given as percentage of the difference between full cooperation and no cooperation without any spillovers.

the case of no spillovers and one exemplary level of spillovers to illustrate the discussion; the argument presented holds for all intensities of spillovers considered in this study.

Without spillovers the payoffs both inside and outside any given coalition rise with the size of the coalition. Inside the coalition the payoff rises because the emission externality is increasingly internalized. Outside the coalition, players free-ride on the abatement effort of the coalition, which becomes increasingly more ambitious as participation rises and thus the benefit of free-riding increases. The curves of inside payoff and outside payoffs intersect before coalition size 3, marking a coalition of 2 as the largest stable coalition.

What changes when spillovers are introduced? Spillovers are restricted to coalition members only, therefore in case of productivity the outside payoff curve remains unchanged. Member payoffs increase with spillovers, thus shifting the inside payoff curve upwards and tilting it to the left because spillovers affect larger coalitions more strongly: there simply are more players benefiting from them. In effect, this moves the intersection of inside and outside payoff curves to the right—participation increases.

Spillovers in mitigation technology shift and tilt the inside payoff curve in the same way, upwards and to the left. However, in contrast to the case of productivity, the outside payoff curve is tilted counterclockwise, too.[5] Whereas productivity of coalition members hardly affects non-members, spillovers in mitigation technology lead to an increased abatement effort by reducing

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[5] We do not observe an upward shift of the outside payoff curve the way the inside payoff curve is shifted. It simply rotates around the fixed-point $(2,0)$ because the outside payoff of a coalition of 2 is simply the non-cooperative equilibrium where there are no spillovers irrespective of the spillover intensity parameter. In contrast, the fixed-point of the tilting inside payoff curve is $(1,0)$, which we observe as a tilting and shift upwards in the range of coalition from 2 to 9.

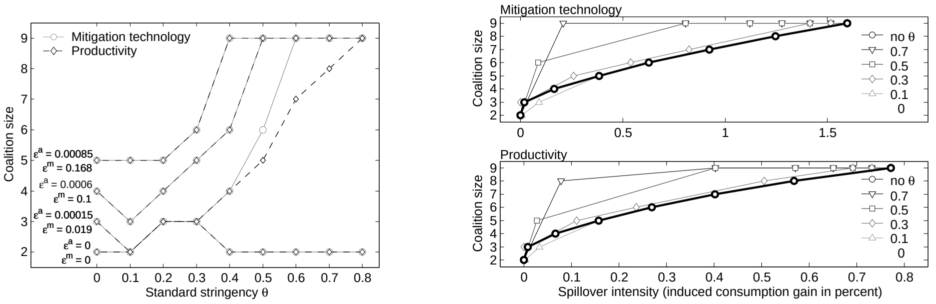

Figure 3: Effect of international standards. The left figure shows the effect of standards on participation for selected spillover intensities. The figures on the right shows the effect of standards on the spillover-participation relationship analogous to Figure 1.

the abatement costs for coalition members. Reduced global emissions, however, have an effect on all players: non-members, too, enjoy these additional emission reductions in form of reduced damages. Thus the positive effect on the inside payoff curve is partially offset by the tilting outside payoff curve—participation is still increased, but less effectively.

Technology Standards

In the following experiments, we combine spillovers with standards, i.e. we introduce standards in a world where simultaneously research cooperation is implemented.

Figure 3 shows participation as a function of the stringency of the technology standard (left). The stringency θ indicates the prescribed reduction of emission intensity relative to emission intensity in non-cooperative equilibrium (Equation 17). Technology standards by themselves (i.e. for $\varepsilon_{ij} = 0$) have very little impact, i.e. participation remains low. A slight increase by one member at $\theta = 0.2$ and $\theta = 0.3$ is not sustained at larger values of θ.[6] Only in combination with spillovers, standards raise participation substantially. Likewise, the positive effect of spillovers on coalition size is strengthened by standards (Figure 3, right).

Why do standards hardly change participation by themselves, but they do enlarge stable coalitions when combined with spillovers? Again, we take a look at payoffs inside and outside the coalitions for mitigation spillovers and productivity spillovers (Figure 4).

Standards guarantee investment in abatement beyond the level of non-cooperative equilibrium without standards. Hence, ambitious standards reduce climate change damages and give all players higher payoffs even in non-cooperative equilibrium or in presence of small coalitions. Compared to the case without standards in Figure 2, payoff in non-cooperative equilibrium (outside payoff for coalition size 2) is now lifted half way towards payoff for fully cooperative behavior (50 percent of the gap between no cooperation and full cooperation).

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[6] Without standards, emission intensity is lower for coalition members compared to non-members. With increasing standards stringency, non-members are forced to abate more. The coalition benefits to the extent that coalitions of three instead of coalitions of two become stable. However, due to (a) the small coalition size and (b) the absence of spillovers, emission intensities within the coalition do not differ much from emission intensities of non-members. Hence with the stringency of standards increasing furthermore, there soon comes a point where standards also affect the abatement behavior of coalition members. This lowers the coalition welfare enough to destabilize the coalition of three. Stability of larger coalitions, or coalitions in calculations with non-zero spillovers are not affected in this way, because the emission intensity within the coalition is lower to begin with and is therefore not affected by standards.

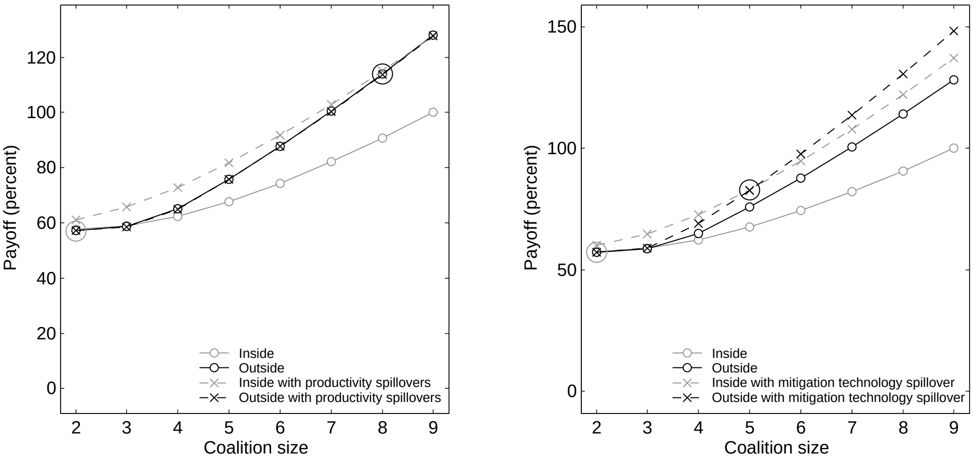

Figure 4: Inside payoff and outside payoff with standards. Analogous to Figure 2, the graphs show inside payoff (received by a member of a coalition of size *n*), which is larger than outside payoff (received by a non-member facing a coalition of size $n - 1$) if the coalition is stable. Spillover on the left are in productivity and in mitigation technology on the right. For stable coalitions the corresponding data points are circled. Payoff is scaled to the gap between no cooperation (0 percent) and full cooperation (100 percent) in the base model without spillovers.

The distance between non-cooperative and fully cooperative solutions has therefore been decreased. In the absence of spillover effects, however, this does not facilitate more participation since the *relative* position of inside and outside payoff curves is not affected, i.e. outside payoff grows more rapidly with coalition size than the inside payoff and soon (at coalition size 3) exceeds it. Spillovers make a difference because, as discussed above, they shift the curve of inside payoffs upwards, thus delaying the interception of the two curves and hence increasing the size of the largest stable coalition.

The argument holds for spillovers in mitigation technology as well as productivity. Again, the latter is more effective in raising participation because here the outside payoff is not affected by spillovers.

3.2. Environmental Effectiveness and Welfare Effects

In the previous section we have seen under which circumstances cooperative R&D and technology standards may raise participation. This section explores the implications of increased participation for environmental effectiveness and for global welfare. We begin the analysis by turning to cooperative R&D.

Cooperative R&D

Figure 5 shows environmental effectiveness relative to socially optimal emission levels in absence of spillovers as the reference point (i.e. 100 percent, whereas emissions from non-cooperative behavior are scaled to 0 percent). Environmental effectiveness increases with spillover intensity in a very similar way to participation (Figure 1), indicating that coalition size is a major determinant and hence a good proxy for environmental effectiveness in this model.

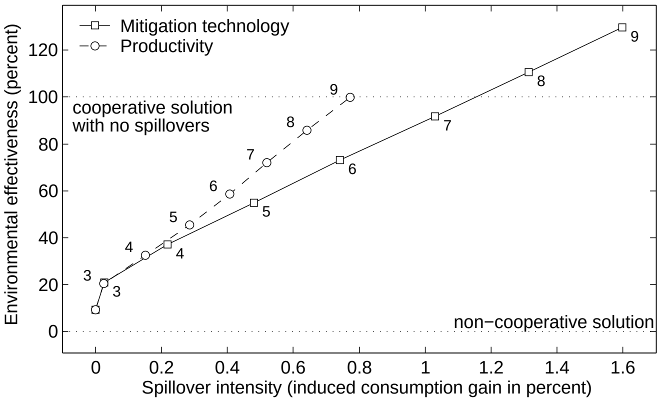

Figure 5: Environmental effectiveness of cooperative R&D. This figure shows environmental effectiveness for stable coalitions, where zero percent is the emission level in absence of spillovers and coalitions, and 100 percent describes socially optimal emissions in an economy without spillovers. Spillover intensity is measured in consumption gain (see Figure 1). We indicate the size of the respective stable coalitions next to the data points.

Note that environmental effectiveness exceeds 100 percent only in case of mitigation technology spillovers but not for spillovers of productivity. The reason is that spillovers in mitigation technology decrease abatement costs and therefore a cleaner environment becomes socially optimal.

The impact of mitigation spillovers on environmental effectiveness offsets some of the drawbacks of mitigation spillovers in terms of participation: Figure 1 stressed that achieving full cooperation required larger spillover intensities in case of mitigation technology. This is also true for environmental effectiveness. However, Figure 5 shows that the difference in spillover intensity to achieve 100 percent environmental effectiveness is less than the difference in achieving full cooperation. Still, productivity cooperation remains the more effective incentive.

Figure 6 shows the welfare effect of stable coalitions. Welfare is normalized to the non-cooperative behavior (0 percent) and full cooperation (100 percent) in an economy without spillovers. Again, we find a similar picture to participation and environmental effectiveness. Participation, or the degree of cooperation, is also a strong determinant of global welfare. Global welfare exceeds 100 percent of welfare without spillovers for both cases of R&D cooperation, highlighting the fact that spillovers are manna from heaven, i.e. compared to an economy without spillovers they provide an additional free income.

Technology Standards

This section explores environmental effectiveness and welfare implications of imposing technology standards. When standards are stringent enough, they might solve the environmental dilemma by themselves irrespective of any cooperation agreements on environment or R&D. We look at the effectiveness and the welfare implications of standards and assess the scope that cooperative agreements have in this setting.

Figure 7 shows the effect of standards on emissions in Nash equilibrium and in case of stable coalitions. When the stringency of the standard is increased, the effect on cumulative global emissions is to bring them down towards their optimal level and below. As cumulative global

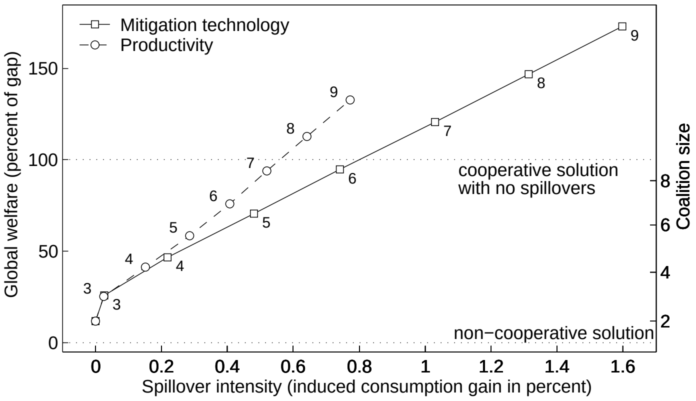

Figure 6: Welfare effects of cooperative R&D. In this figure we show how global welfare of stable coalitions increases with spillover intensity (measured in consumption gain, see Figure 1). Much of the effect is due to rising participation (see Figure 1), hence we indicate coalition size next to the respective data points.

emissions approach their optimum levels, so does global welfare (Figure 7). However, welfare stops short of its optimum level and begins to decline when cumulative emissions reach the level of optimum cumulative emissions. This is due the fact that the timing of emission intensity reduction prescribed by the standards are not cost-effective. It is the inefficiency of standards as a policy instrument manifesting in this figure. This disadvantage of command and control instruments like standards compared to market or price incentive based instruments is well known (see e.g. Requate, 2005). Indeed any of the levels of cumulative emissions in the previous figure could likely be reached at lower costs and higher global welfare if the timing of emission intensity reduction was not prescribed but chosen optimally.

Cooperative agreements on environment and R&D can bridge this gap: Figure 3 includes welfare levels for a number of coalitions that are stable at the given standard stringency due to including cooperative R&D (spillovers) in the agreement. Standards that fall short of enforcing

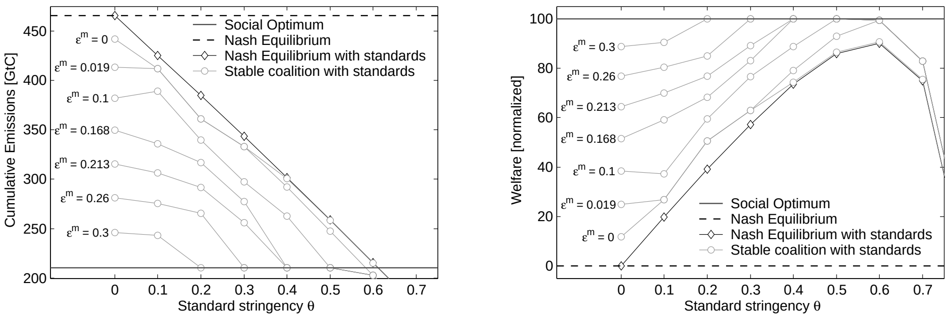

Figure 7: Effects of standards on cumulative emissions (left) and welfare (right). Stable coalitions are induced by spillovers of mitigation technology, the spillover parameter ε^m is included next to the corresponding curves.

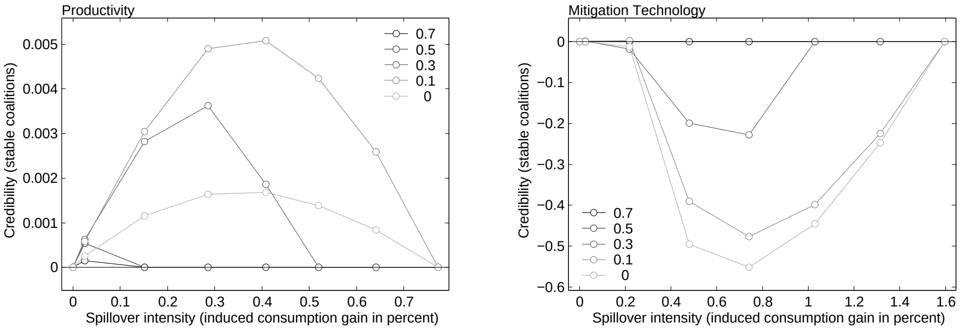

Figure 8: Credibility of restricting spillovers to coalition members. We compute credibility as the difference of coalition members' welfare with restricted spillovers minus the case of spillovers to all regions, hence positive values imply credibility.

optimal emission levels and are inefficient to begin with, may still be sufficient to induce full cooperation in combination with some spillovers. We observe that often the standards that were necessary to stabilize full cooperation are exceeded under full cooperation—otherwise standards would distort the optimal solution resulting in below-optimal welfare levels.

3.3. Credibility of Exclusive R&D Cooperation

Restricting spillovers to coalition members is only credible if coalition members are not worse off compared to the case where knowledge is public, i.e. spillovers are unrestricted. Hence we investigate the credibility of exclusive R&D cooperation by comparing it to a scenario where R&D spillovers extend to all regions and not just coalition members. We continue to assume that only coalition members participate in R&D cooperation, i.e. spillovers extend to non-members but not vice versa.

Figure 8 shows whether restricting spillovers to the coalition is beneficial to its members. Values are plotted for different stringencies of standards and only for stable coalitions. In case of productivity we find that threatening exclusiveness is credible for all stable coalitions, and all unstable coalitions as well (not shown). There is no advantage for coalition members in boosting productivity for non-members. Quite the contrary, the increased productivity would entice non-members to produce and pollute more.

Excluding non-members from spillovers of R&D in mitigation technology is almost always a non-credible threat for stable coalitions (Figure 8, right). Coalition members benefit from letting spillovers extend to non-members, because the spillovers add to non-member abatement and further reduce the emission intensity and actual emissions of the non-members. Coalition members then benefit from reduced climate change damages. This is a crucial difference to productivity spillovers that do not have this feedback onto the coalition.

For both kinds of spillovers, credibility approaches zero for small as well as for large coalitions and exhibits a maximum for medium coalition sizes. This depends on the extent of spillovers to non-members: the smaller coalitions are, the lower the number of players generating spillovers. On the other end of the spectrum, the larger the coalition, the lower the number of non-members receiving spillovers.

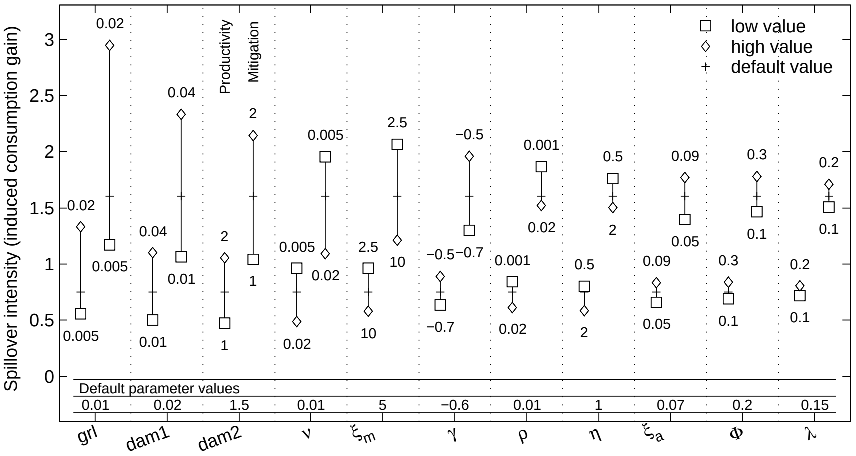

Figure 9: Spillover intensities that support full cooperation. We show the impact of parameter variation on the effectiveness of research cooperation by giving the lowest spillover intensity that induces full cooperation. Results for cooperation on productivity and mitigation are shown side by side for each parameter; numbers above and below data points indicate the low and high values used.

4. Sensitivity of Key Results

This section explores the sensitivity of key results towards variation of input parameters. Central results of the preceding sections are that TOA may sustain full cooperation depending on the spillover intensity, and that linking to productivity cooperation is generally more effective in raising environmental cooperation than linking to cooperative research on mitigation.

We explore in how far these results continue to hold when parameter values change by running *high* value and *low* value scenarios for key parameters. An assessment of global sensitivities, i.e. a simultaneous variation of all parameters, would be preferable because it accounts for the fact that sensitivity of the results for variation of one parameter will in general depend on all other parameters. We stick with an exploration of local sensitivities to limit the computational burden.

Figure 9 shows results from these low value/high value calculations. Using full cooperation as a reference point, Figure 9 reports the spillover intensity necessary for the grand coalition of all players to be stable. The first message from this figure is that in all variations, either full cooperation was sustained by raising spillover intensities or was even achieved at lower spillover intensities. Thus, R&D cooperation proves to be a sufficiently strong incentive for all parameter values in these variations. More importantly though, the spillover intensities necessary to achieve full cooperation via cooperative mitigation research are always higher than in case of the corresponding calculation featuring cooperation on productivity. Hence, this finding is also robust with respect to our parameter variations.

Table 1 summarizes our choice of high and low parameter values and also reports the impact of these parameter variations on more key results. The difference between cooperation on productivity versus mitigation is measured by the “difference in incentives” in columns 6-7, reported

		Parameter values			Diff. in Incentive		Env. Effect.		Welfare Effect	
Parameter	Symbol	Default	Low	High	Low	High	Low	High	Low	High
Pure rate of time preference	ρ	0.01	0.001	0.02	1.03	0.91	24.7	39.6	40.0	44.1
Elasticity of marginal utility	η	1.0	0.5	2.0	0.96	0.92	25.7	40.3	40.5	44.2
Growth rate of labor supply	grl	0.01	0.005	0.02	0.61	1.62	27.1	41.8	42.6	40.2
Rate of decarbonization	ν	0.01	0.005	0.02	1.00	0.61	47.3	14.5	40.6	41.6
Effectiveness of investments in km	ξ_m	5.0	2.5	10.0	1.11	0.63	39.6	22.5	42.1	39.9
Effectiveness of investments in a	ξ_a	0.07	0.05	0.09	0.74	0.93	27.1	32.2	41.2	40.7
Stepping on toes effect	λ	0.15	0.1	0.2	0.79	0.91	28.7	31.3	40.3	41.3
Standing on shoulders effect	Φ	0.2	0.1	0.3	0.77	0.94	27.9	32.5	41.3	40.6
Abatement cost exponent	$-\gamma$	0.6	0.5	0.7	0.66	1.07	21.2	43.4	35.4	48.7
Damage function exponent	$dam2$	1.5	1.0	2.0	0.57	1.09	42.6	23.2	42.3	40.0
Damage function coefficient	$dam1$	0.02	0.01	0.04	0.56	1.23	39.5	22.6	41.3	40.8

Table 1: Parameter values and effectiveness difference. Columns 3-5 list the default, low, and high parameter values. Columns 6-7 report the difference in spillover intensity between cooperation on mitigation and productivity to achieve full cooperation. For default parameters this value is 0.85, the metric for spillover intensity is induced consumption gain, see Figure 1. Columns 8-9 and columns 10-11 report the corresponding difference in environmental effectiveness and global welfare, respectively. Here, the default values are 30.0 and 41.5, respectively.

as the difference in spillover intensities that are sufficient to stabilize full cooperation. In Figure 1 this is the distance between the topmost data points of mitigation cooperation and productivity cooperation on the *x*-axis. This difference is considerably affected by parameter changes, mostly in the range of plus/minus thirty percent of the default, yet it is always positive and larger than 0.5 percent, indicating that R&D cooperation on productivity remains significantly more effective than cooperation on mitigation R&D.

Similarly, columns 8-9 show the difference in environmental effectiveness for the same stable grand coalitions from Figure 9. We take the metric of environmental effectiveness from Figure 5, i.e. the numbers in this table measure the difference of the topmost data points in Figure 5 on the *y*-axis. Analogously, columns 10-11 show the impact of parameter variation on the difference in global welfare of grand coalitions, i.e. the distance of the topmost data points in Figure 6 on the *y*-axis. The values in columns 8-11 of Table 1 show that even though parameter variation has a considerable impact, our conclusions remain intact.

5. Summary and Conclusions

We assessed different technology oriented agreements (TAO) in a conceptual model and had to resort to numerical solutions. Naturally, any conclusions from these result about the economy described by the model must be taken with a grain of salt. Nevertheless, the model suggests some rather general differences between the selected TOA, which we summarize in the following.

Cooperative R&D in mitigation technology is less effective because via emissions reductions, spillovers of mitigation technology raise both, the coalition payoff and the free-rider incentive. This feedback of mitigation reduces the positive incentive of spillovers on coalition formation making cooperative R&D that is unrelated to emission abatement a more attractive option for setting incentives for participation.

Contrary to R&D in productivity, R&D in mitigation technology has a positive impact on the environment by reducing abatement costs. Indeed the same level of environmental effectiveness can be reached with smaller coalitions using R&D cooperation in mitigation technology rather than productivity. Nevertheless, the spillover intensity necessary to reach this same level of environmental effectiveness is larger than in case of productivity.

Moreover, our model suggests that restricting spillovers exclusively to the coalition is non-credible in case of mitigation technology. This is plausible because in a world with a global warming problem, it is desirable to let advanced mitigation technology diffuse as much as possible. Overcoming non-credibility due to economic reasons may be possible by means exogenous to this model, for example by commitment (e.g. Houba and Bolt, 2002, Ch. 7), which could be enforced by reputation or eliminating the alternatives. Nevertheless, this is a complication that is absent in productivity spillovers.

This impact of the source of spillovers could be one of the reasons why Nagashima and Dellink (2008) only find small effects of spillovers related to marginal abatement costs, whereas Botteon and Carraro (1998) observe a significant increase of participation up to full cooperation due to spillovers that reduce production costs.[7]

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[7] Of course, the models used in Botteon and Carraro (1998) and Nagashima and Dellink (2008) differ in many respects from this model, among them are: a different modeling framework, heterogeneity of players, and inclusion of transfers within the coalition. The feedback of a stronger abatement effort (due to lower abatement costs) onto non-members ought to be present in the model nonetheless. It is also not clear how the assumed spillover intensities in the different models compare.

We argued that if technology standards are easier to agree upon than a cooperative environmental agreement, then adopting an agreement on standards may be a helpful first step towards an international environmental agreement. Our model suggests that this works when standards cause emission reductions for non-members but are fulfilled voluntary by coalition members. Here, this is the case only when at least some cooperative R&D is carried out, setting the abatement levels of members and non-members far enough apart.

A combination of technology standards and cooperative R&D is also promising for a second reason. International standards by themselves reduce emissions in a way that is not cost efficient. Combined with cooperative R&D, however, they may induce environmental cooperation to an extent beyond standards, therefore making its inefficiency unimportant.

Limitations

This study aimed to identify general cause-effect relationships in the interplay of TAO and IEA. The simplifying assumptions of (ex ante) identical regions and lack of technological detail facilitated the analysis, but at the same time they reduce the scope of its conclusions for real world policy. Therefore, testing the lessons learnt from this study in models with heterogeneous regions and explicit technology choice would be a step to confirm them and elaborate on their implications.

In particular, we analyzed the interaction of standards and spillovers from a purely macroeconomic perspective, arguing that standards come into force due to incentives that are exogenous to the model. Recent integrated assessment models (e.g. Bosetti et al., 2006) resolve some technological detail providing the basis to implement standards on the technology level and allow to explore the scope of the results of this paper in a less conceptual setting.

Moreover, we argued that the spillover extent could be fostered through governmental programs, assuming that this is possible at no additional societal costs. While this assumption is backed by the very idea of R&D spillovers, namely that R&D generates particularly high returns, it does not account for crowding out of other R&D.

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Appendix A. Parameter Choices

Table A.2 lists our choice of parameters. We restrict this study to the case of symmetric players, hence a calibration to real world regions is out of question. Nevertheless we selected a set of parameters that is plausible in light of the empirical literature. This appendix lists the assumptions we made.

Parameter ξ_a drives endogenous growth. We chose its value such that economic output shows a 2.5 percent annual growth in the first century.

Parameters in the climate module are based on literature values, giving us a 3°C temperature increase by 2100, and a 7.5°C increase by 2200 in non-cooperative equilibrium and business as usual, i.e. without climate change damages.

The damage function was chosen such that in non-cooperative equilibrium damages in 2100 are 6 percent. Within the mitigation option, parameters γ and ξ_m were selected such that optimal abatement (the social optimum solution) reduces the temperature increase in 2100 to 2.4°C.

Table A.2: Parameter values.

Parameter	Symbol	Value
Pure rate of time preference	ρ	0.01
Elasticity of marginal utility	η	1
Income share capital	β	0.35
Growth rate of labor supply	grl	0.01
Exogenous rate of decarbonization	ν	0.01

Table A.2: Parameter values.

Parameter	Symbol	Value
Initial labor	l_0	1
Initial labor productivity	a_0	1
Initial capital stock	k_0	34
Effectiveness of investments in *a*	ξ_a	0.023
Effectiveness of investments in *km*	ξ_m	5.0
Abatement cost exponent	γ	0.2
Ocean biosphere as CO_2 source	β^P	0.47
Atmospheric retention factor	B	1.51e-3
Radiative temperature driving factor	μ	8.7e-2
Temperature damping factor	α^P	1.7e-2
Ocean biosphere as CO_2 sink	σ^P	2.15e-2
Initial concentration	$conc_0$	377
Initial temperature	$temp_0$	0.41
Initial cumulative emissions	$cume_0$	501
Damage function coefficient	$dam1$	0.02
Damage function exponent	$dam2$	1.5