Economic Modelling 26 (2009) 641–649

Contents lists available at ScienceDirect

Economic Modelling

journal homepage: www.elsevier.com/locate/econbase

The effects of tariffs on coalition formation in a dynamic global warming game

Kai Lessmann *, Robert Marschinski, Ottmar Edenhofer

Potsdam Institute for Climate Impact Research, P.O. Box 60 12 03, 14412 Potsdam, Germany

ARTICLE INFO

Article history:
Accepted 13 January 2009

JEL classification:
C61, Optimization Techniques, Programming Models, Dynamic Analysis
C72, Noncooperative Games
H41, Public Goods
Q54, Climate, Natural Disaster
Q58, Government Policy

Keywords:
Climate change
Self-enforcing international environmental agreements
Trade sanctions
Coalition stability
International cooperation

ABSTRACT

The prospects for cooperation on climate protection beyond 2012 are currently uncertain. Thus policy instruments which foster participation in International Environmental Agreements (IEA) are in demand. Among the instruments under discussion are trade sanctions. Multi-region optimal growth models are a state of the art tool for integrated assessment, but introducing trade sanctions distorts the competitive equilibrium, making it difficult to compute numerically. We introduce trade and trade sanctions into a model of coalition stability to assess the potential of trade sanctions to support an IEA. Trade is modeled by having all countries produce a generic output good, but adopting national product differentiation (Armington assumption). Coalitions are free to impose tariffs on imports from non-cooperating countries. We solve the model numerically using a refined version of Negishi's [Negishi, T., 1960. Welfare economics and existence of an equilibrium for a competitive economy. Metroeconomica 12, 92–97] basic algorithm. We then apply the model to analyze the influence of tariffs on international cooperation. The model suggests that there is indeed a significant potential to raise participation through trade sanctions, even when goods from different countries are nearly perfect substitutes. Furthermore we investigate the effect of trade sanctions on global welfare, environmental effectiveness, and the credibility of the tariff mechanism.

1. Introduction and motivation

Combining elements of the economic, the energy and the climate system, Integrated Assessment Models (IAMs) have become an indispensable formal tool in the realm of climate policy analysis. There are numerous examples, ranging from Nordhaus' (1994) seminal DICE model to the latest generation of regionalized models featuring high levels of sectoral and technological detail.[1]

A prominent class within the IAM family consists of optimal growth models; these build on a tradition going back to Ramsey (1928), and view accumulation and economic growth as driven by agents' intertemporally optimized investment decisions. Examples include the RICE/DICE family of models (Nordhaus, 1994; Nordhaus and Yang, 1996), and its modifications such as FEEM-RICE (Bosetti et al., 2004) or ENTICE (Popp, 2004), as well as the MIND (Edenhofer et al., 2005) and DEMETER (Gerlagh, 2006) models.

Two main aspects justify the use of intertemporal optimization in the context of climate policy: First, Edenhofer et al. (2006) argue that this framework is appropriate whenever the research question requires an economic model to be run over long time horizons and to capture structural changes. Indeed, inertia in the climate system requires to adopt time horizons of more than a century. Second, Turnovsky (1997, pp. 3), arguing from a more theoretical point of view, backs the intertemporal utility maximization of a representative agent as the preferred way to give macroeconomic models a firm micro-foundation and make them suitable for welfare analysis. Although critics point to the fact that assumptions such as perfect foresight and strict rationality are actually at odds with reality, results from such models retain their usefulness (at least) in terms of a first-best benchmark.

To come closer to the political reality of a world consisting of self-interested and sovereign nation states, optimal growth models, just like other IAMs, have over time passed from a uni-regional world[2] representation to a decentralized multi-regional[3] formulation. Unfortunately, even the sole introduction of emissions trade comes at the cost of a substantial aggravation of the numerics required to compute competitive equilibria. The calculation of trade flows and price vectors would in principle be straightforward with Negishi's (1960) algorithm. But in the presence of an externality like the climate feedback, an appropriate modification of the algorithm is required.[4] The additional effort is, of

* Corresponding author. Tel.: +49 331 2882563; fax: +49 331 2882640.
E-mail address: lessmann@pik-potsdam.de (K. Lessmann).

[1] See, for example, Kypreos and Bahn (2003), Barker et al. (2006), Crassous et al. (2006), Bosetti et al. (2006).

[2] E.g. DICE (Nordhaus, 1994) and MIND (Edenhofer et al., 2005).

[3] E.g. RICE (Nordhaus and Yang, 1996) and WITCH (Bosetti et al., 2006).

[4] Implementing trade in these models is challenging (Nordhaus and Yang, 1996; Eyckmans and Tulkens, 2003). Nordhaus and Yang (1996) mention that "a major cause of the long gestation period of this research has been the difficulty in finding a satisfactory algorithm for solving the intertemporal general equilibrium".

0264-9993/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.econmod.2009.01.005

course, justified by the need to estimate the regional distribution of climate damages and mitigation costs, as well as by the new possibility to compute scenarios in which only a group of nations—a 'climate coalition'—decides to cooperate on climate change.

In our work we follow the multi-regional modeling approach and formally extend it in two ways: first, international trade in goods is introduced by dropping the common assumption[5] that all countries produce the same perfectly substitutable good; instead we assume that goods are differentiated according to their place of origin.[6] This approach—sometimes referred to as Armington assumption—is often encountered[7] in CGE modeling and allows to reproduce international cost spillovers from mitigation policies.[8] Second, we introduce another feature that is incompatible with the basic Negishi approach, namely a tax distortion in form of a punitive tariff duty.

The first part of the paper emphasizes the formal aspects of solving such a model structure for a competitive equilibrium. We describe our solution approach that draws on work by Kehoe et al. (1992) and Leimbach and Edenhofer (2007), and illustrate how a validation of the competitive equilibrium is obtained.

To demonstrate the usefulness of the model set-up, an application to a current issue in climate policy is presented in the second part of the paper. Namely, we analyze the scope for regional cooperation—that is, the viability of a 'climate coalition'—and investigate whether tariffs can help to increase participation in such a coalition.

This question seems timely in view of the currently meager prospects for full international cooperation after the expiry of the Kyoto Protocol in 2012. Indeed, a lively debate has emerged on the scope for regional cooperation, and various supportive policy instruments have been brought up in the literature, such as R&D protocols (Barrett, 2003; Carraro et al., 2002), a technology fund (Benedick, 2001), a Marshall Plan (Schelling, 2002), and, last but not least, trade sanctions (e.g. Aldy et al., 2001).

The use of trade restricting tariff duties has been proposed in the form of energy or CO_2 border tax adjustments, with the double objective to deter free-riding and to ease the loss of competitiveness for coalition members. The debate has so far focused on the question of whether tariffs are feasible under legal (Biermann and Brohm, 2005) and implementation (Ismer and Neuhoff, 2007) aspects. However, another question is whether their employment would be credible, given that orthodox economic theory suggests that the distortionary effects of tariffs would be welfare depressing for all parties.

More specifically, Stiglitz (2006) proposes to raise participation in a climate treaty by imposing trade sanctions against non-signatories. He argues that this is possible and even required in the legal framework of the World Trade Organization (WTO): products from countries that allow unconstrained emissions are implicitly subsidized which warrants to prohibit or tariff the import of such products. Perez (2005) gives a detailed analysis of the legal implications of such a proposal concluding that recent precedents (the so-called "shrimp decision") suggest that the WTO will not interfere with such tariffs. Similar to these trade sanctions, Nordhaus (1998) proposes border tax adjustments to enforce compliance with harmonized carbon taxes.

The effects of trade sanctions on coalition formation have also been analyzed within formal models (Barrett, 1997; Finus and Rundshagen, 2000), albeit to lesser extent. As mentioned before, the widely used optimal growth models do not naturally accommodate trade in goods (other than emissions trade), and are therefore normally unsuitable for an analysis of the effects of tariffs. Thus, existing formal studies of trade sanctions and international cooperation either utilize a static modeling framework (Barrett, 1997) or Computable General Equilibrium (CGE) models (Kemfert, 2004).

For the purpose of this paper, we apply the model in a stylized—that is, not empirically calibrated—form in order to explore the scope for tariffs in international cooperation. We find that under the assumption of price—as well as tariff-taking behavior of all countries, the imposition of tariffs on non-coalition members unequivocally raises the scope for international cooperation. However, the coalition's welfare gains start to decline once the tariffs go beyond a certain threshold, and—at a still higher level—tariffs actually become welfare decreasing and thus lose credibility. We interpret the observed effects as a consequence of the model's representation of international trade: when each country's representative output good can only be imperfectly substituted by goods from other countries, but all countries must behave as price-takers, then the tariff constitutes an indirect price setting mechanism, which helps coalition countries to capitalize on their implicit market power and increase their terms-of-trade. However, similar to an optimum tariff rate or monopoly price, the benefits from this increase start to vanish once the tariff exceeds a certain level.

In line with economic theory our model shows that the introduction of tariffs distorts the otherwise efficient markets, and hence, global welfare would be higher without tariffs. We find, however that these losses are easily offset by the gains of increased cooperation that are induced by these tariffs. With respect to environmental effectiveness, we find that in our model carbon leakage is small, i.e. emission increases in free-riding countries do not outweigh the abatement effort of the coalition.

Although we employ the model and the algorithm in an exemplary way in order to explore the scope for tariffs in coalition formation, it can be easily extended to other research questions, e.g. to investigate the effects of differentiated border tax adjustments (BTA) on coalition formation, or to analyze the long-term structural effects of different (optimal, non-optimal) carbon taxes.

The remaining part of the paper is organized as follows: The next section presents the model; Section 3 explains the solution algorithm. In Section 4, we discuss its application to coalition stability in a model with import tariffs, and Section 5 concludes.

2. Model structure

We begin by stating the problem: we introduce a multi-actor growth model with climate change damages and tariffs on trade flows.

2.1. Preferences

Each region i is modeled following Ramsey (1928), i.e. the maximization of discounted utility endogenously determines the intertemporal consumption-investment pattern.

$$\text{welfare}_i = \int_0^\infty e^{-\rho t} l_{it} U(c_{it} / l_{it}) \mathrm{d}t \tag{1}$$

Instantaneous utility U is an increasing and concave function of per capita consumption c/l. It is weighted with the region's total population l and discounted with a rate of pure time preference ρ.

In a world where goods from different countries are imperfect substitutes, utility depends on the consumption of both domestic c^{dom} and foreign goods c^{for}, which are combined into a so-called Armington aggregate via a CES (Constant Elasticity of Substitution) function.

$$c_{it} = \left[s^{\text{dom}} \left(c_{it}^{\text{dom}} \right)^{\rho A} + \sum_j s_j^{\text{for}} \left(c_{ijt}^{\text{for}} \right)^{\rho A} \right]^{(1/\rho A)} \tag{2}$$

The elasticity $\sigma^A > 0$ is determined by the parameter $\rho^A \in (0,1)$ according to $\sigma^A = 1/(1-\rho^A)$. Share parameters s^{dom} and s_j^{for}

[5] E.g. in the RICE (Nordhaus and Yang, 1996) and WITCH (Bosetti et al., 2006) models.
[6] This model of international trade is discussed, e.g., in Feenstra et al. (2001).
[7] E.g. Bernstein et al. (1999), Kemfert (2002).
[8] In models without trade, one country's carbon constraint bears no economic consequences for other countries. This seems contradictory when thinking of shifts in competitive advantage and specialization ('carbon leakage'), as well as of the negative consequences for some countries if fossil fuel demand plunges.

characterize the relative preference for domestic and foreign goods and add up to one.

2.2. Technology

We assume a macroeconomic production function F of the Cobb–Douglas form that depends on two input factors, capital stock k and labor supply l.

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

Hence, technology is constant-returns-to-scale and with decreasing marginal productivity in both factors. The productivity parameter a grows exogenously at the constant rate gr and thus incorporates labor-augmenting technological progress.

$$\frac{\mathrm{d}}{\mathrm{d}t}a_{it} = gr \cdot a_{it} \tag{4}$$

While labor is given exogenously, capital can be accumulated by investment:

$$\frac{\mathrm{d}}{\mathrm{d}t}k_{it} = in_{it} \tag{5}$$

2.3. Climate dynamics

Greenhouse gas emissions e are generated as a byproduct of production. The autonomous decrease of emission intensity at a constant rate ν may be enhanced by investments im in abatement capital km. Parameter $iekm$ determines the investments' efficiency.

$$e_{it} = \sigma_{it}\, y_{it} \exp(-\nu t) \tag{6}$$

$$\sigma_{it} = (1 + km_{it})^{-\psi}, \quad \psi > 0 \tag{7}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}km_{it} = iekm \cdot im_{it} \tag{8}$$

The climate system is represented in a stylized way based on Petschel-Held et al. (1999). The total stock of atmospheric greenhouse gases ce grows due to the instantaneous emissions of all countries

$$\frac{\mathrm{d}}{\mathrm{d}t}ce_t = \sum e_{jt} \tag{9}$$

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

$$\frac{\mathrm{d}}{\mathrm{d}t}conc_t = Bce + \beta^P \sum e_{jt} - \sigma^P(conc_t - conc_0) \tag{10}$$

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

$$\frac{\mathrm{d}}{\mathrm{d}t}temp_t = \mu \log(conc_t / conc_0) - \alpha^P(temp_t - temp_0) \tag{11}$$

Similar to Nordhaus and Yang (1996), temperature changes cause climate change damages, destroying a fraction $1-\Omega$ of economic output:

$$\Omega_{it} = 1 / \left(1 + dam1_i(temp_t)^{dam2_i}\right) \tag{12}$$

$$y_{it} = \Omega_{it}F(k_{it}, l_{it}) \tag{13}$$

2.4. Trade and tariffs

We impose an intertemporal budget constraint enforcing that export value and import value are ultimately balanced.

$$\int_0^{\infty} \sum_j p^m_{ijt} m_{ijt} \mathrm{d}t = \int_0^{\infty} \sum_j p^x_{ijt} x_{ijt} \mathrm{d}t \tag{14}$$

Imports received by i from j are denoted by m_{ij}, exports from i to j by x_{ij}. Naturally, imports and exports that describe the same trade flow must be the same, hence $m_{ijt} = x_{jit}$. Imports become foreign consumption goods after import tariffs—if any—have been deducted in the form of iceberg costs.

$$c^{\text{for}}_{ijt} = \left(1 - \tau_{ij}\right) m_{ijt} \tag{15}$$

$$tr_{ijt} = \tau_{ij} m_{ijt} \tag{16}$$

Tariff revenues tr are recycled without the consumer realizing the origin of the revenues. We close the economy by stating the physical budget constraint, which balances the available economic output with consumption, both investment options, and exports to the rest of the world.

$$y_{it} = c_{it} + in_{it} + im_{it} + \sum_j x_{ijt} \tag{17}$$

Finally, we need to update the Armington equation (Eq. (2)) to incorporate the tariff revenue tr.

$$c_{it} = \left[s^{\text{dom}} \left(c^{\text{dom}}_{it}\right)^{\rho A} + \sum_j s^{\text{for}}_j \left(c^{\text{for}}_{ijt} + tr_{ijt}\right)^{\rho A} \right]^{(1/\rho A)} \tag{18}$$

3. Solving for a Nash equilibrium

The model features two distortions preventing that competitive equilibrium and social planner solution coincide: climate change damages caused by emissions, and import tariffs. In this section, we describe an algorithm that finds a Nash equilibrium for such models.

Our approach to compute a competitive equilibrium builds on Negishi (1960), Kehoe et al. (1992), and Leimbach and Edenhofer (2007). For a discussion of algorithmic alternatives we refer to Leimbach and Edenhofer (2007). Negishi (1960) shows that a competitive equilibrium maximizes a particular social welfare function which is a weighted sum of the utility functions of the individual consumers. Hence maximization of such a social welfare function may be used to compute a competitive equilibrium. Similarly, Kehoe et al. (1992) use joint maximization to compute competitive equilibria but extend the scope to economies with externalities. They analytically demonstrate the equivalence of a set of optimization problems and the competitive equilibrium.

To find an equilibrium, we iterate individual welfare maximization for all players in addition to a maximization of aggregate social welfare, an approach similar to the one proposed by Leimbach and Edenhofer (2007). We do so by fixing variables of the optimization problems at previously determined levels.

3.1. Finding a Nash equilibrium

To solve our model for a Nash equilibrium, we repeat the following three steps until convergence is reached.

- Step 1
  We start by finding a Nash equilibrium in emissions $e = \{e_t\}, e_t = (e_{1t}, \ldots, e_{Nt})$ which are determined by the investment decisions in production capital in and abatement capital im, i.e. we solve a fix point problem

$e = G(e)$ where G is the self-interested response of players to other players' emission trajectories. We compute G by solving

$$\forall_i \quad \max_{\{in_{it}, im_{it}\}} \text{welfare}_i$$
$$\text{subject to} \quad \text{Equations } 1-13,\ 15-18 \text{ and } m_{ijt} = \overline{m_{ijt}},\ x_{ijt} = \overline{x_{ijt}},\ e_{kt} = \overline{e_{kt}} \text{ for } k \neq i$$

with trade flows m_{ijt} and x_{ijt} and other players' emissions e_{kt} fixed to their previous levels, as indicated by the bars.

- Step 2
  Next, we search for a competitive equilibrium in trade flows (m, x) with $m = \{m_t\}$, $m_t = (m_{ijt})$ and $x = \{x_t\}$, $x_t = (x_{ijt})$, while keeping the emission externality fixed at the level $\overline{e}$ found in Step 1. This is done by solving the fix point problem $tr = H(tr)$, with $tr = \{tr_t\}$, $tr_t = (tr_{ijt})$, and H the response of the social planner to a given tariff revenue constraint $\overline{tr}$. H is computed by solving the joint optimization

$$\max_{\{in_{it}, im_{it}, m_{ijt}, x_{ijt}\}} \sum \delta_i \text{ welfare}_i$$
$$\text{subject to} \quad \text{Equations } 1-13,\ 15,\ 17-18 \text{ and } e_{it} = \overline{e_{it}}, \text{tr} = \overline{\text{tr}}$$

  The parameters δ_i represent the regions' weights within the joined social welfare function, and are also referred to as Pareto or Negishi weights.
- Step 3
  By using price information derived from the Lagrange multipliers of the maximization problem, we determine deficits and surpluses in the intertemporal budget constraints (Eq. (14)). We balance the budgets by adjusting the welfare weights δ_i and repeating Steps 1–3.

Convergence is reached when the intertemporal budget is in balance and the fix point equations in Steps 1 and 2 are satisfied.

3.2. Numerical verification of the Nash equilibrium

We verify the resulting 'candidate' Nash equilibrium strategies in emissions and trade numerically by comparing them to the results of the following maximization problems:

$$\forall_i \quad \max_{\{in_{it}, im_{it}, m_{ijt}, x_{ijt}\}} \text{welfare}_i$$
$$\text{subject to} \quad \text{Equations } 1-18 \text{ and prices } p^m_{ijt}, p^x_{ijt}$$

which include the budget (Eq. (14)) with market prices from the final model solution. Deviations of this model from our solution should be within the order of magnitude of numerical accuracy only, which is what we find (not shown). In particular, simultaneous clearance of all international markets confirms the Nash equilibrium in international trade.[9]

3.3. Partial agreement Nash equilibria

For the application of this algorithm to self-enforcing International Environmental Agreements (IEA), we need to extend the algorithm from plain Nash equilibrium to Partial Agreement Nash Equilibrium (PANE). Whereas in the Nash equilibrium there is no cooperation, PANE defines partial cooperation as socially optimal behavior among a subset of players (the coalition). PANE is a Nash equilibrium of the coalition (acting as one player) and all non-members. Within the coalition, a utilitarian social welfare function, i.e. the equally weighted sum of all individual welfare functions, is maximized.

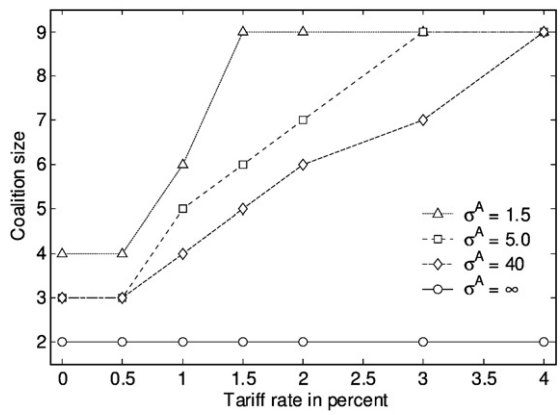

Fig. 1. Largest stable coalitions for a given tariff.

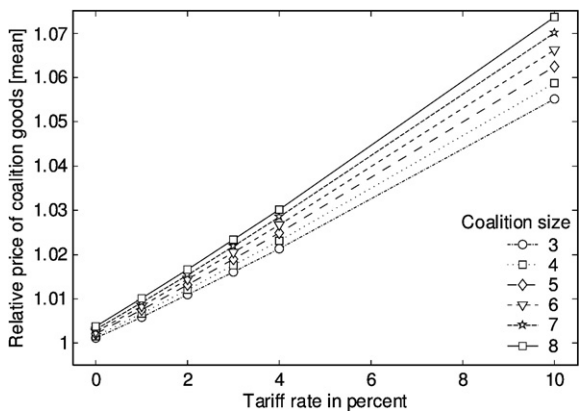

Fig. 2. Relative price of coalition goods.

4. Application to international cooperation on climate change

In this section we apply our model to the analysis of import tariffs as a trade sanction against non-signatories of an International Environmental Agreement (IEA). Following the literature on self-enforcing IEA (e.g. Carraro and Siniscalco, 1992; Barrett, 1994), we consider coalitions that are internally and externally stable, i.e. members of the coalition cannot improve their situation by leaving the coalition and joining the group of non-members which free-ride on the effort of the remaining coalition, and neither do non-members have an incentive to join the coalition.

To avoid the black-box effect and to facilitate an interpretation of the qualitative effects produced by the model, we restrict the following analysis to the symmetric case of nine perfectly identical countries.

4.1. Results

4.1.1. Tariff's influence on participation

Our model confirms that tariffs are potentially an effective instrument to increase the scope for international cooperation: participation in the coalition becomes unambiguously higher when a tariff on imports from non-member countries is applied. This result is illustrated in Fig. 1: in the absence of tariffs, the largest stable coalition has only three or four members, while a tariff rate between 1.5 to 4% is sufficient to induce full cooperation.

[9] Note that we do not attempt to show uniqueness of the identified equilibrium. Indeed, Kehoe et al. (1992) demonstrate how general equilibrium models are prone to multiplicity in the presence of externalities. However, they also show that this occurs when the externality is rather large. In our case, where tariffs and climate damages are on the scale of percents and ten percent, respectively, we assume that the issue of multiple equilibria is still negligible. This is corroborated by the fact that our numerical simulations produced robust results without indication of multiple equilibria.

This effect can be understood in the light of the model's representation of international trade, in which each region produces an imperfectly substitutable good and hence disposes—not at the firm, but at the country level—of some market power.[10] In effect, a small tariff on imports from non coalition-members exploits this market power and leads to a rise in the relative price of goods produced by coalition members (see Fig. 2). The latter obtain a net benefit from this positive terms-of-trade effect, similar in its mechanics to what is known from the analysis of optimal tariffs or monopolistic pricing. Since by assumption only coalition members can apply such a tariff, it constitutes an incentive to join the coalition.

Note that the relative price of coalition goods also rises just as a function of the size of the coalition, even in the absence of any tariff (Fig. 2 at $\tau=0$). This happens because the emission cuts realized by coalition countries diminish their output, and hence there is—with respect to the business-as-usual—a reduced supply of coalition goods. If demand is inelastic ($\sigma^A<\infty$), the relative price must consequently go up. In fact, the possibility to pass on mitigation costs to free-riders via such terms-of-trade effects also explains how larger coalitions can be 'stabilized' even without tariffs by simply decreasing the elasticity of substitution to a sufficiently low level, as seen in Fig. 1 at $\tau=0$.

The graph in Fig. 1 also shows that the effectiveness of tariffs is reduced in the presence of higher elasticities of substitution. For example, a tariff of 1 percent induces a stable coalition with six out of nine member countries when $\sigma^A=1.5$, five members when $\sigma^A=5$ and four members when $\sigma^A=40$. Since a higher elasticity implies higher substitutability and hence lower market power, this behavior is fully consistent with our explanation. Indeed, in case all goods are perfect substitutes ($\sigma^A=\infty$) , the tariff loses its clout entirely, as expected.

4.1.2. Environmental effectiveness of cooperation

A common argument brought forward against climate coalitions with incomplete membership is the leakage problem: the effectiveness of any collective effort by the coalition could be undermined, if not annihilated, by free-riders who increase their emissions in response to the coalition's reductions. As Fig. 3 illustrates, the extreme case of 100% leakage rate is not present in our model. Instead we observe that an increase in the coalition size unambiguously results in a reduction of cumulative global emissions. Free-riding does cause some leakage, but the extent is limited and would not warrant the discouragement of cooperation between a subset of countries (Fig. 4).

The missing indication of the parameter values for τ and σ^A in Figs. 3 and 4 hints at another behavioral characteristic of the model: emission trajectories are fully determined by the coalition size, and do not depend on the Armington elasticities or the tariff rate.[11] Perhaps counterintuitive, this observation is actually in line with the model assumptions: we defined utility as the logarithm of a linearly homogeneous function, which, by using the indirect utility function and an exact price index, can be rewritten as a sum of two terms, the first related to the output level, and the second to the relative prices and the elasticity of substitution. Price changes induced by a tariff or a change in σ^A have an influence only on the latter, but do not change the optimal capital accumulation and, as a direct consequence, output levels and emissions remain the same.

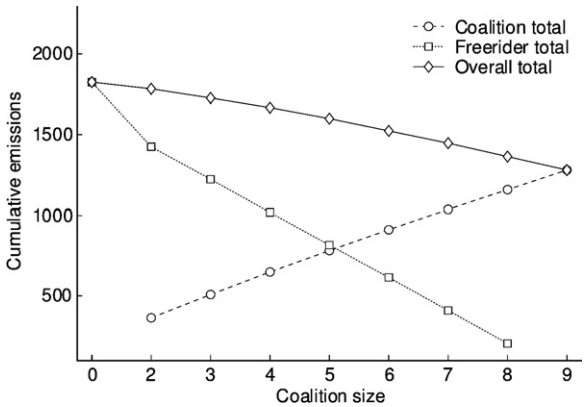

Fig. 3. Effect of coalition formation on total cumulative emissions.

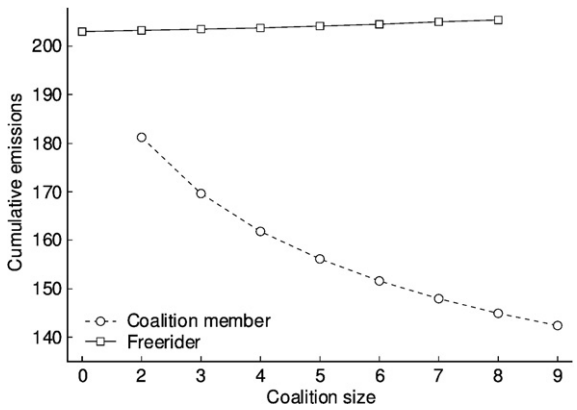

Fig. 4. Average free-rider and coalition member emissions as function of coalition size.

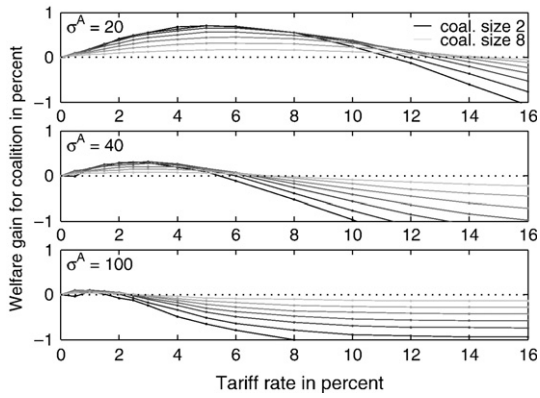

Fig. 5. Credibility of imposing tariffs.

4.1.3. Credibility of tariffs

Threatening to impose tariffs is only credible if the coalition is better off with than without tariffs.[12] Within our model characterized by national product differentiation, tariffs provide an indirect means for coalition countries to exploit their implicit market power. Thus, a tariff should be beneficial as long as it is not too high, the limit depending on the elasticity of substitution. This intuition is confirmed in Fig. 5, which shows how a coalition's welfare changes with increasing tariffs.

[10] In this context, market power is to be understood as an aggregate property of whole countries, and is due to the fact that each country's representative output bundle is somewhat different. However, there is no monopolistic market structure as such, since the firms making up each country's economy always behave competitively. In fact, *all* Nash equilibria in this study represent competitive equilibria based on price-taking behavior.

[11] The coalitions' stability of course depends on their value.

[12] This concept of credibility is rather shortsighted: when considering only the welfare effects of tariffs on themselves, coalition members ignore that tariffs may increase participation and thus bring about net positive welfare effects even when 'incredible' according to this concept. This shortsightedness is, however, consistent with the employed shortsighted concept of stability.

As expected, welfare initially increases, but starts to decline after reaching a maximum value and eventually drops below zero. The threshold value at which the welfare effect becomes negative marks the maximum tariff rate that is still credible.

Although the observed qualitative pattern is robust with respect to parameter changes, the specific value of the maximum tariff as well as the potential welfare gain depend on the elasticity of substitution σ^A and on the coalition size: both increase with lower elasticities and smaller coalition sizes. For example, at $\sigma^A = 20$ tariff rates of less than 10% are credible for any coalition size, while at $\sigma^A = 100$ the cut-off is already at about 2%. This dependence on σ^A can again be explained in terms of the greater market influence that can be realized with a lower elasticity. The observable higher welfare gain for *smaller* coalitions is a consequence of higher tariff revenues: in the presence of large coalitions, there are only few free-riders left whose goods are actually subject to tariff duties, while there are payments from almost all trading partners if the coalition has only two members.

4.1.4. Welfare implications of tariffs

Tariffs have an ambiguous effect on global welfare: on the one hand they can increase global welfare because they enhance the scope for cooperation. On the other hand—as free trade advocates might object—they distort free trade and thus undermine global efficiency, which ought to cause a loss of welfare which could in the worst case outweigh the gains. We compare the two opposing effects in Figs. 6 and 7.

Fig. 6 shows gains induced by tariffs measured as the difference in global welfare between the largest stable coalition with a given tariff rate and the largest stable coalition in the absence of tariffs.[13] As can be seen, the welfare gains are quite significant and reach up to 65 to 80% for full cooperation, depending on the coalition size and corresponding welfare levels without tariffs (see Fig. 1).

In contrast, the welfare losses caused by the distortionary effects of tariffs are shown in Fig. 7. They are measured by taking the largest stable coalition at each tariff rate and computing the increase in global welfare achieved by dropping all tariffs (ignoring that the coalition may not be stable anymore). In agreement with standard economic theory the graph shows welfare losses that increase steadily with the tariff rate. However, the welfare losses due to the trade distortion are one order of magnitude smaller than the gains achieved by furthering cooperation. In normative terms, this suggests that the trade distorting effect of tariffs should be an acceptable price to pay in exchange for more inclusive climate coalitions.[14]

4.2. Sensitivity analysis

A central result in the previous section was that a tariff levied on imports from free-rider countries in the order of magnitude of a few percent sustains full cooperation on emissions reduction. In this section, we explore in how far this result continues to hold when the values of the model's key input parameters are systematically changed to *high value* and *low value* estimates. In order to keep the computational costs manageable, we stick to an exploration of local sensitivities.[15]

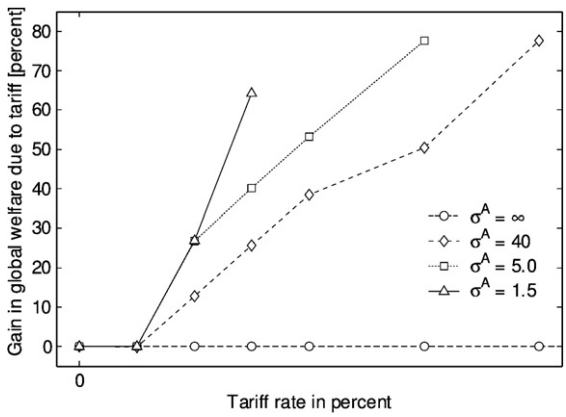

Fig. 6. Gains in global welfare due to tariffs.

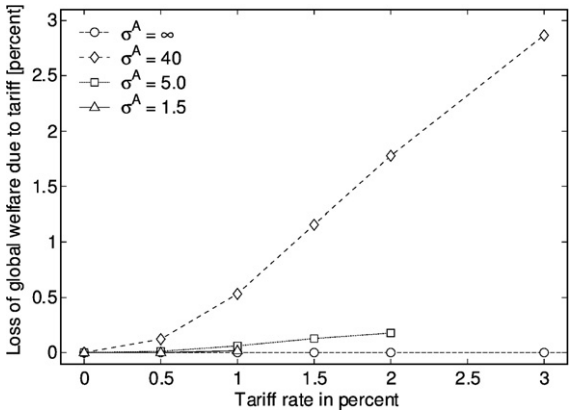

Fig. 7. Losses in global welfare due to tariffs.

Fig. 8 reports sensitivities obtained from the variation of nine parameters. Indicated are the lowest tariff rates that still support full cooperation for the chosen parameter values. The numerical values for high and low are reported next to the data-point, while the parameters' name and default value is given at the bottom of the figure. The results show that for all parameter variations, full cooperation can still be achieved by adjusting the tariff rate. Furthermore, the required tariff rate does not exceed five percent for our selection of low and high values.

Barrett's (1994) conclusion that cooperation is harder to achieve when it is most needed helps to understand the sensitivities. The largest impact is exerted by the rate of pure time preference ρ, which is known to have a strong impact on growth and the (associated) emissions: patience boosts savings leading to more production. Additionally, the weight of future damages is increased. Varying parameters of the damage function immediately lessens or exacerbates the need for coordinated mitigation. Also the next two most sensitive parameters, the exogenous rates of decarbonization ν and productivity growth gr are again closely related to emissions and economic growth, and therefore the urgency of environmental cooperation.

In addition to the local sensitivity analysis, we also explore the consequences of a structural change in the model: in Eq. (4) we assumed exogenous technological progress, at the constant rate gr. Alternatively, we might follow the concept of Jones and Williams (1998) and depict the productivity parameter a as a knowledge stock that evolves endogenously according to

$$\frac{\mathrm{d}}{\mathrm{d}t} a_{it} = gr(iea \cdot ia_{it})^{\lambda}(a_{it})^{\phi} \tag{19}$$

[13] Normalized (in both figures) to the scale defined by the welfare gap between the Nash equilibrium and social optimum.

[14] It might seem counterintuitive that welfare losses in Fig. 8 are higher when goods are better substitutes, especially since in the limit case $\sigma^A \to \infty$ tariffs become ineffective and hence welfare losses drop to zero. The intuition behind this effect is as follows: Tariffs have two effects, an income effect and a substitution effect. The income effect (due to the price increase of coalition goods) is predominantly of distributional nature, leaving global welfare largely unaffected. The substitution effect, on the other hand, causes a decline in the total volume of world trade, which bears welfare costs for all countries. This deviation from the socially optimal trade volume increases with higher elasticities of substitution, and thus becomes more pronounced for large values of σ^A.

[15] Our approach is similar—albeit much more concise—to the sensitivity analysis of the DICE model in Nordhaus (1994, Ch. 4). Parameter variations leading to Nordhaus' alternative high values are comparable to ours. Moreover, five of the eight identified most sensitive parameters have counterparts in our analysis. As one difference, in our study the uncertainty of climate dynamics is solely assessed by varying the damage function.

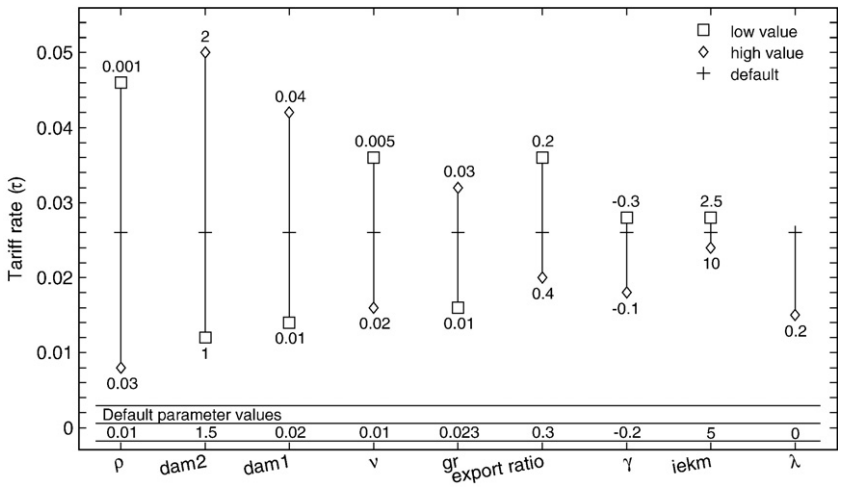

Fig. 8. Local sensitivity analysis. The figure shows how the tariff rate necessary to induce full cooperation changes when key input parameters are replaced by lower or higher values.

The new control variable *ia* represents R&D investments[16], *iea* their efficiency, and λ and ϕ parameters for "stepping on toes" and "standing on shoulders" effects, respectively.[17] To test the influence of endogenous technological change, we choose $iea = 1.7e3$, $\lambda = 0.15$, and $\phi = 0.2$, which reproduces the average growth rate of the default model with exogenous technological change. The latter case is recovered from Eq. (19) by setting $\lambda = 0$, $\phi = 1$. The impact of this structural change is no larger than the parameter variations (see last column in Fig. 8).

In the main part of this paper, we restrict the analysis to symmetric regions. This greatly reduces the number of computations needed to determine the largest stable coalition: for n symmetric regions, n model evaluations suffice (in our case 9), whereas n heterogeneous regions require $2^n - n$ model runs (in our case 503). In Table 1 we take one step towards heterogeneous regions by exploring the impact of "stylized" heterogeneity. To this end, we define three different scenarios with heterogeneous parameters.

First, scenario 1 (row 4) incorporates heterogeneity by assigning each region a different amount of initial capital k_0. As can be seen, even though the poorest and richest regions differ by a factor 20, the effect on the tariff rate needed to induce full cooperation is all but negligible. Indeed, cooperation becomes a little easier.

Heterogeneity should constitute a more serious obstacle to cooperation when there are some regions with high damages and high mitigation costs (high interest in cooperation) and some with low damages and low mitigation costs (low interest in cooperation). This hypothesis is tested in scenarios 2 and 3, shown in rows 5–6 (moderate heterogeneity) and 7–8 (strong heterogeneity), where the damage and mitigation cost parameters have were set accordingly.

We find that this type of heterogeneity does not prevent full cooperation either, even though higher tariff rates are necessary. Whether the increased level of tariffs is due to heterogeneity remains an open question: both the damages and mitigation costs are determined through nonlinear functions. Hence, even though we varied the parameters such that their average value across all countries remains the same, average damages and average mitigation costs may well have changed due to the introduction of heterogeneity.

5. Conclusions

This study makes a methodological and a policy contribution to the integrated assessment modeling of climate change. We present a model in the tradition of multi-regional optimal growth models that includes trade relationships between regions. Including climate damages and punitive tariffs introduces two external effects into the model. Thus the competitive equilibrium will fail to be socially optimal and a more elaborate approach than social welfare maximization is necessary to find an equilibrium solution.

We address this challenge by presenting an algorithmic extension to the approaches by Negishi (1960) and Kehoe et al. (1992). We illustrate model and algorithm by applying the model to the current issue of trade sanctions as an instrument to foster participation in an international environmental agreement. We find:

- When the coalition imposes tariffs on imports from free-riding regions, participation in the coalition rises. Global social welfare rises along with participation despite small welfare losses due to the distortion caused by the tariff instrument.
- To threaten non-members with trade sanctions is credible as long as the tariff rate is small, where 'small' depends on the Armington elasticity. For large tariff rates coalition members would be better off not to sanction trade.
- Non-members respond to emission cuts on the part of the coalition by raising their own emissions, but we find this leakage effect to be small.

These results are comprehensible in light of the underlying theoretical model of international trade: following the concept of national product differentiation, goods produced by different regions are assumed to be imperfect substitutes among each other. Yet all countries act as price takers in a competitive equilibrium. Introducing tariffs in this context allows coalition members to capitalize on their potential market power. The elasticity of substitution between goods determines the ease with which non-members can avoid coalition goods, and hence puts a limit on the potential clout of the tariff instrument.

The application of the model nevertheless identifies some robust qualitative relationships and clearly demonstrates the usefulness of the algorithm. In fact, the treatment of externalities sketched in this paper can easily be transferred to similar dynamic games with externalities. Finally, in order to put numbers on the identified qualitative effects, heterogeneous regions should be introduced and be calibrated to real world regions. This would further enhance the policy relevance of the model results.

Acknowledgements

We would like to thank Carlo Carraro, Michael Finus, Carsten Helm, and Britta Tietjen for discussions of an earlier draft of this paper, and two anonymous referees for their comments. All remaining errors are, of course, our own. The model experiments made extensive use of the

[16] Of course, these investments need to be deducted from the budget in Eq. (15).
[17] See Jones and Williams (1998) for a detailed discussion of the equation.

Table 1
Impact of heterogeneity.

Parameter	Scenario	Region									Tariff
		1	2	3	4	5	6	7	8	9	τ
dam2		1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	0.028
iekm	Default	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	
k_0		34.0	34.0	34.0	34.0	34.0	34.0	34.0	34.0	34.0	
k_0	1	3.4	11.1	18.7	26.4	34	41.7	49.3	57.0	64.6	0.026
dam2	2	1.75	1.69	1.63	1.56	1.5	1.44	1.36	1.31	1.25	0.034
iekm		4.0	4.25	4.5	4.75	5	5.25	5.5	5.75	6	
dam2	3	2	1.88	1.75	1.63	1.5	1.38	1.25	1.13	1.0	0.042
iekm		3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	

The last column shows the smallest tariff rate τ that is sufficient to induce full cooperation; τ was varied between 0.01 and 0.05 using a step size of 0.002. Only parameter values that differ from their defaults in rows 1–3 are listed, i.e. scenario 1 shows a variation of initial capital k_0, scenarios 2 and 3 show experiments that effect mitigation costs (via iekm) and climate change damages (via dam2).

SimEnv (Flechsig et al., 2008) multi-run simulation environment. Kai Lessmann and Robert Marschinski received funding from the European Commission within the ADAM project (project 018476-GOCE).

Appendix A. Parameter choices

Table 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 such as to produce a scenario that appears plausible. This appendix lists the assumptions we made.

The choice of the pure rate of time preference has received much attention since Stern (2007) suggested a significantly lower value (0.001) than earlier studies, e.g. 0.03 in Nordhaus and Yang (1996). We strike middle ground by selecting $\rho = 0.01$, but explore both Stern's and Nordhaus' choices in our sensitivity analysis.

We chose the rate of exogenous labor enhancing technological change *gr* such that long term economic growth averages at 2.1%/year, which is within the range of the IPCC SRES family of development scenarios (IPCC, 2000).

With initial labor and labor productivity at 1.0, we chose initial capital such that the savings rate is approximately constant at 23% during the first decades, i.e. the economy is on a balanced growth path. This figure corresponds to the world's empirical average of 23% between 1990 and 2002 (Bank for International Settlements, 2004, 28).

Table 2
Parameter values.

Parameter	Symbol	Value
Pure rate of time preference	ρ	0.01
Income share capital	β	0.35
Labor productivity growth	gr	0.023
Rate of autonomous emission intensity reduction	ν	0.01
Initial labor	l_0	1
Initial labor productivity	a_0	1
Initial capital stock	k_0	34
Share parameter, domestic	s^{dom}	See text
Share parameter, foreign	s^{for}	See text
Armington elasticity of substitution	ρ^A	0.975
Effectiveness of investments in *km*	*iekm*	5.0
Abatement cost exponent	ψ	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

We frequently vary the Armington parameter σ^A that determines the elasticity of substitution in our experiments using values between 1.5 and 40. We compare these result to the limit case of an infinite σ^A and explore the transition to the limit using a high value of $\sigma^A = 100$. In calibrated real-world models these elasticities typically lie between 1 and 8 (Bernstein et al., 1999). To enhance the comparability of calculations with different ρ^A we selected the share parameters s^{dom} and s^{for} such that for all ρ^A the export ratio is about 30% in the Nash equilibrium. For 2005, the WTO has estimated the ratio of exports in goods and commercial services to GDP as 29% (WTO, 2007, 30).

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 the business as usual, i.e. without climate change damages and without any cooperation between regions. Nordhaus and Yang (1996) estimate a similar temperature increase of 3.06 °C in 2100 for their market scenario.

The damage function was chosen such that in Nash equilibrium damages in 2100 are 6%. We chose this relatively high value (compared to damages ranging from 0 to about 5.5% across regions in RICE with a global average of about 3%) to account for Stern's (2007) estimation that "[business as usual] climate change will reduce welfare by an amount equivalent to a reduction in consumption per head of between 5 and 20 percent."

Within the mitigation option, parameters ψ and *iekm* were selected such that optimal abatement (the social planner solution) reduces the temperature increase in 2100 by 0.6 °C. In Nordhaus and Yang (1996), cooperative behavior reduces global temperature in 2100 by 0.22 °C.

References

Aldy, J.E., Orszag, P.R., Stiglitz, J.E., 2001. Climate change: an agenda for global collective action. Prepared for the conference on The Timing of Climate Change Policies, Pew Center on Global Climate Change.
Bank for International Settlements, 2004. Annual Report 2004/05. http://www.bis.org/publ/arpdf/ar2005g2.pdf.
Barker, T., Haoran, P., Köhler, J., Warren, R., Winne, S., 2006. Decarbonising the global economy with induced technological change: scenarios to 2100 using E3MG. The Energy Journal 27, 143–160.
Barrett, S., 1994. Self-enforcing international environmental agreements. Oxford Economic Papers 46, 878–894.
Barrett, S., 1997. The strategy of trade sanctions in international environmental agreements. Resource and Energy Economics 19, 345–361.
Barrett, S., 2003. Environment and Statecraft: The Strategy of Environmental Treaty-Making. Oxford University Press, Oxford.
Benedick, R.E., 2001. Striking a new deal on climate change. Issues in Science and Technology 18 (1), 71–76.
Bernstein, P.M., Montgomery, W.D., Rutherford, T.F., 1999. Global impacts of the Kyoto Agreement: results from the MS-MRT model. Resource and Energy Economics 21, 375–413.
Biermann, F., Brohm, R., 2005. Implementing the Kyoto Protocol without the United States: the strategic role of energy tax adjustments at the border. Climate Policy 4 (3), 289–302.
Bosetti, V., Carraro, C., Galeotti, M., 2004. The dynamics of carbon and of energy intensity in a model of endogenous technical change. Fondazione Eni Enrico Mattei, May.

Bosetti, V., Carraro, C., Galeotti, M., Massetti, E., Tavoni, M., 2006. WITCH: a world induced technical change hybrid model. The Energy Journal, Special Issue Hybrid Modelling of Energy Environment Policies: Reconciling Bottom-up and Top-down, pp. 13–38.
Carraro, C., Siniscalco, D., 1992. Strategies for the international protection of the environment. Journal of Public Economics 52, 309–328.
Carraro, C., Buchner, B., Cersosimo, I., Marchiori, C., 2002. Back to Kyoto? US Participation and the linkage between R&D and climate Cooperation. CESifo Working Paper Series No. 688; FEEM Working Paper No. 22.2002.
Crassous, R., Hourcade, J.C., Sassi, O., 2006. Endogenous structural change and climate targets modeling experiments with Imaclim-R. Energy Journal 27, 259–276.
Edenhofer, O., Bauer, N., Kriegler, E., 2005. The impact of technological change on climate protection and welfare: insights from the model MIND. Ecological Economics 54 (2–3), 277–292.
Edenhofer, O., Lessmann, K., Kemfert, C., Grubb, M., Koehler, J., 2006. Induced technological change: exploring its implications for the economics of atmospheric stabilization — synthesis report from the innovation modeling comparison project. Energy Journal, Special Issue Endogenous Technological Change and the Economics of Atmospheric Stabilisation, pp. 57–107.
Eyckmans, J., Tulkens, H., 2003. Simulating coalitionally stable burden sharing agreements for the climate change problem. Resource and Energy Economics 25, 299–327.
Feenstra, R.C., Markusen, J.R., Rose, A.K., 2001. Using the gravity equation to differentiate among alternative theories of trade. Canadian Journal of Economics 34 (2), 430–447.
Finus, M., Rundshagen, B., 2000. Strategic links between environmental and trade policies if plant location is endogenous. Diskussionsbeitrag Nr. 283, Diskussionsbeitrag des Fachbereichs Wirtschaftswissenschaften der FernUniversität Hagen.
Flechsig, M., Böhm, U., Nocke, T., Rachimow, C., 2008. The Multi-Run Simulation Environment SimEnv. Version 2.01. See http://www.pik-potsdam.de/software/simenv/.
Gerlagh, R., 2006. ITC in a global growth-climate model with CCS. Energy Journal, Special Issue: Endogenous Technological Change and the Economics of Atmospheric Stabilisation, pp. 55–72.
IPCC, 2000. Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press.
Ismer, R., Neuhoff, K., 2007. Border tax adjustment: a feasible way to support stringent emission trading. European Journal of Law and Economics 24 (2), 137–164.
Jones, C.I., Williams, J.C., 1998. Measuring the social return to R&D. Quarterly Journal of Economics 113, 1119–1135.
Kehoe, T.J., Levine, D.K., Romer, P.M., 1992. On characterizing equilibria of economies with externalities and taxes as solutions to optimization problems. Economic Theory 2, 43–68.
Kemfert, C., 2002. An integrated assessment model of economy-energy-climate — the model Wiagem. Integrated Assessment 3 (4), 281–298.
Kemfert, C., 2004. Climate coalitions and international trade: assessment of cooperation incentives by issue linkage. Energy Policy 32, 455–465.
Kypreos, S., Bahn, O., 2003. A MERGE model with endogenous technological progress. Environmental Modeling and Assessment 8, 249–259.
Leimbach, M., Edenhofer, O., 2007. Technological spillovers within multi-region models: Intertemporal optimization beyond the Negishi approach. Economic Modelling 24, 272–294.
Negishi, T., 1960. Welfare economics and existence of an equilibrium for a competitive economy. Metroeconomica 12, 92–97.
Nordhaus, W.D., 1994. Managing the Global Commons. MIT Press, Cambridge, Massachusetts.
Nordhaus, W.D., 1998. Is the Kyoto Protocol a dead duck? Are there any live ducks around? Comparison of alternative global tradable emissions regimes, cited in: Barrett, S., Stavins, R., 2003: Increasing Participation and Compliance in International Climate Change Agreements. International Environmental Agreements: Politics, Law and Economics 3, 349–376.
Nordhaus, W.D., Yang, Z., 1996. A regional dynamic general-equilibrium model of alternative climate-change strategies. The American Economic Review 86, 741–765.
Petschel-Held, G., Schellnhuber, H., Bruckner, T., Tóth, F.L., Hasselmann, K., 1999. The tolerable windows approach: theoretical and methodological foundations. Climatic Change 41, 303–331.
Perez, O., 2005. Multiple regimes, issue linkage, and international cooperation: exploring the role of the WTO. University of Pennsylvania Journal of International Economic Law 26, 735–778.
Popp, D., 2004. ENTICE: endogenous technological change in the DICE model of global warming. Journal of Environmental Economics and Management 48 (1), 742–768.
Ramsey, F., 1928. A mathematical theory of saving. Economic Journal 38, 543–559.
Schelling, T.C., 2002. What makes greenhouse sense? Time to rethink the Kyoto Protocol. Foreign Affairs 81 (3), 2–9.
Stern, N., 2007. The Economics of Climate Change: The Stern Review. Cambridge University Press.
Stiglitz, J.E., 2006. Making Globalization Work. W.W. Norton & Company, New York.
Turnovsky, S.J., 1997. International Macroeconomic Dynamics. MIT Press.
WTO, 2007. International Trade Statistics 2007. WTO Publications, Geneva, Switzerland.