DISCUSSION PAPER SERIES

No. 4412

ECONOMIC AND ENVIRONMENTAL EFFECTIVENESS OF A TECHNOLOGY-BASED PROTOCOL

Barbara Buchner and Carlo Carraro

INTERNATIONAL TRADE

Centre for Economic Policy Research

www.cepr.org

Available online at: www.cepr.org/pubs/dps/DP4412.asp

ISSN 0265-8003

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Barbara Buchner, Fondazione ENI Enrico Mattei
Carlo Carraro, Università di Venezia, Fondazione ENI Enrico Mattei and CEPR

Discussion Paper No. 4412
June 2004

Centre for Economic Policy Research
90–98 Goswell Rd, London EC1V 7RR, UK
Tel: (44 20) 7878 2900, Fax: (44 20) 7878 2999
Email: cepr@cepr.org, Website: www.cepr.org

CEPR Discussion Paper No. 4412

June 2004

ABSTRACT

Economic and Environmental Effectiveness of a Technology-based Protocol*

This Paper provides a first applied game theory analysis of a technology-based climate protocol by assessing: (i) the self-enforcement (namely, the absence of incentives to free ride) of the coalition that would form when countries negotiate on climate-related technological cooperation; (ii) the environmental effectiveness of a technology-based climate protocol. The analysis is carried out using a model in which endogenous and induced technical changes are explicitly modelled and in which international technological spillovers are also quantified. The results of our analysis partly support Barrett's and Benedick's conjecture. On the one hand, a self-enforcing agreement is more likely to emerge when countries cooperate on environmental technological innovation and diffusion than when they cooperate on emission abatement. Technological cooperation – without any commitment to emission control – may not lead to a sufficient abatement of greenhouse gas concentrations, however.

JEL Classification: C70, H00, H40 and O30
Keywords: agreements, climate, incentives, policy and technological change

Barbara Buchner
Fondazione Eni Enrico Mattei
Campo S. Maria Formosa, Castello 5252
30122 Venezia
ITALY
Email: buchner@feem.it

Carlo Carraro
Dipartimento di Scienze Economiche
Università di Venezia
San Giobbe 873
30121 Venezia
ITALY
Tel: (39 041) 234 9166
Fax: (39 041) 234 9176
Email: ccarraro@unive.it

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*This Paper is part of the research work being carried out by the Climate Change Modelling and Policy Unit at Fondazione Eni Enrico Mattei. The authors are grateful to Scott Barrett, Michael Grubb, Billy Pizer, Laurent Viguier, Marzio Galeotti, Stefan Schleicher, Efrem Castelnuovo, Carmen Marchiori, Igor Cersosimo and the participants at the ESRI Meeting of the Collaboration Projects, Tokyo, February 26-28, 2003 and at the IFRIRFF Workshop on 'How to Make Progress Post-Kyoto', Paris, March 19, 2003, for helpful suggestions and remarks. The usual disclaimer applies.

Submitted 06 April 2004

Economic and Environmental Effectiveness of a Technology-based Climate Protocol

1. Introduction

Climate change control is a global governance problem. Any strategy to control climate change will only be effective if adopted by as many countries as possible, or at least by a number of countries which account for a large share of total emissions. However, due to the absence of a supra-national authority that can enforce environmental policies and regulations on a global scale, climate change control can only be achieved via voluntary initiatives and international agreements among sovereign countries.[1]

In the context of climate change, the Kyoto Protocol was welcomed as an important achievement in international diplomacy, because, for the first time, it succeeded in establishing binding emissions reduction targets for industrialised countries. However, the US decision not to ratify the Protocol has largely reduced its environmental effectiveness, thus inducing all countries to adapt their own climate strategy to a new scenario in which some major current and potential future greenhouse gas emitters do not cooperate on emission control.

The Kyoto process currently appears to be in a deadlock. The US and Russia have not yet ratified the Protocol. Therefore, the conditions for it to come into force have not yet been met.[2] Even if the Kyoto Protocol does come into force, its environmental effectiveness will be very limited. Therefore, a number of alternative proposals designed to increase the environmental effectiveness of an international climate agreement have emerged. At the same time, countries have in recent years begun to adopt domestic policy measures and to sign bilateral and multilateral deals to enhance investments in R&D and the diffusion of climate-related technologies.

This latter fact demonstrates that agreements on environmental technological cooperation are easier to sign and implement than agreements on emission abatement. This is not surprising because cooperation on technological innovation and diffusion is less affected by free-riding incentives than

[1] This basic point identifies the boundaries of most analyses of international negotiations on climate change. See Barrett (2002) for a survey.

[2] A precondition of the Kyoto Protocol being enforced is that at least 55 Parties to the Convention, representing at the same time at least 55% of 1990 carbon dioxide emissions of Annex B Parties, must have ratified the treaty. After the US withdrew from the Protocol, the participation of certain countries – as e.g. Russia – has thus become crucial. The outcome of the COP 7 in Marrakech includes considerable concessions to Russia in order to provide additional incentives for Russia to ratify. However, Russia is still delaying its decision to ratify.

cooperation on emission abatement (Cf. Carraro and Siniscalco, 1995, 1997; Yi, 1997). Therefore, it would be important to explore whether a generalised global agreement on technological cooperation could be the right approach to deal with climate change control.

This idea has been proposed in a number of recent policy studies (Cf. Barrett, 2001 and 2002; Benedick, 2001), which claim that a technology-based climate protocol could be self-enforcing, i.e. it could be signed by all or almost all countries worldwide. However, albeit self-enforcing – a property which is unlikely to be shared by climate regimes where cooperation concerns emission control – a technology-based climate regime may not be environmentally effective. The reason for this is that while, on the one hand, cooperation on climate-related technological innovation and diffusion reduces emissions per unit of output, abatement costs and therefore global GHG emissions, on the other hand, investments in R&D, as well as the adoption of new technologies and new standards, stimulate economic growth both in developed and developing countries, thus increasing global emissions. The outcome of these two combined effects cannot easily be assessed using only a theoretical framework. A quantitative analysis becomes necessary in order to verify whether the adoption of a technology-based climate regime actually reduces GHG emissions. This is the key objective of this paper.

Using the FEEM-RICE model – a modified version of Nordhaus and Young's (1996) RICE model – we will make an initial assessment of the environmental and economic benefits of a technology-based protocol, and in particular of whether the total amount of global emissions is actually reduced by the adoption of an international agreement in which all countries find it profitable to cooperate on technological innovation and diffusion.

We proceed as follows. In section 2, we present an overview of recent climate initiatives and developments in climate policy. Section 3 describes recently developed policy proposals designed to overcome some of the shortcomings of the Kyoto Protocol. In particular, we present the main features of Barrett's (2001, 2002) and Benedick's (2001) proposal. In section 4, we use the FEEM-RICE model to examine whether a technology-based climate regime would actually yield economic benefits and increase environmental effectiveness. The final section draws some policy conclusions.

2. Climate negotiations and bilateral technological agreements

In spite of the US decision to withdraw from the Kyoto Protocol, several climate initiatives have been developed both within and outside the Kyoto policy framework. On the one hand, in several Annex B countries measures to achieve the Kyoto targets have been adopted (e.g. the EU Directive on emission trading or the Japanese climate plan). On the other hand, the US has implemented a domestic climate policy designed to achieve a –18% reduction in energy intensity.[3] In addition, negotiations with Russia are under way and could provide sufficient incentives for Russia to ratify the Kyoto Protocol in the near future.

Most importantly from the point of view of this paper, in recent years a large number of bilateral agreements on technology and scientific cooperation have been signed between various countries throughout the world.

For example, the European Union cooperates on international scientific policy with almost 30 countries[4] and the US is engaged in a large number of joint technology projects as well.[5] In particular, a variety of proposals on technology development projects have emerged in the context of climate change control.

At COP 9 in Milan, the US Department of Energy presented two new reports from the US Climate Change Technology Program, stressing the three pillars of the US strategy on climate change: science, technology and international cooperation. The reports discuss a portfolio of federal R&D investments in climate change technology development and emphasise that research into innovative technologies – such as hydrogen, bio-energy, carbon sequestration – will address the issue of climate change by devising "a path to stabilising atmospheric GHG concentrations" and ensuring "secure, affordable, and clean energy to power economic growth world-wide".[6]

These research activities are to be undertaken both domestically and in cooperation with other countries, as is already demonstrated by the various bilateral climate technology agreements signed between the US and other nations. For example, the "US-Australia Climate Action Partnership" is an initiative consisting of various programs aimed at improving the scientific cooperation in areas

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[3] The plan – announced in February 2002 and presented in greater detail at COP 9 in Milan – to lower the US greenhouse gas intensity by –18% over the next 10 years in order to slow the growth of GHG emissions per unit of economic activity is analysed in De Moor et al. (2002), Goulder (2002), Viguier (2002). Although President Bush's Climate Change Initiative implies a very modest US emissions reduction target, it represents at the same time an acknowledgement of the long-term character of the climate change problem and thus improves the prospects for a US participation in international efforts to combat climate change (White House, 2002).

[4] In particular, the EU has signed science and technology cooperation agreements with Argentina, Australia, Brazil, Canada, Chile, China, India, Japan, Russian Federation, South Africa, Tunisia, Ukraine, United States, a S&T agreement with New Zealand and has formed RTD associations with Bulgaria, Cyprus, Czech Republic, Estonia, Hungary, Iceland, Latvia, Lithuania, Malta, Norway, Poland, Romania, Slovakia, Slovenia and Turkey. For further information see http://europa.eu.int/comm/research/iscp/countries.html

[5] Currently, the US has signed agreements for scientific and technological cooperation with 34 countries and the European Union. For further information on the activities of the Office of Science and Technology Cooperation established by the US Department of State see http://www.state.gov/g/oes/stc/.

[6] For more information on the US Climate Change Technology Program and its reports see http://www.climatetechnology.gov/.

including climate change science, reduced emissions strategies and engagement with business on technology to reduce GHG emissions (News.com.au, July 2nd, 2002, CO2e.com, July 7th, 2002). A similar partnership exists between the US and Japan and aims at promoting joint projects and exchanging opinions on various measures to prevent global warming (CO2e.com, April 5th, 2002). On the same basis, agreements for technology cooperation have been signed between the US and Russia (Pravda, Jan. 17th, 2003), as well as between the US and Italy, India and China.

The European Union is also engaged in a number of technology agreements aimed at the improvement of energy technologies and more generally at the development of climate friendly production processes. For example, an agreement with China on strengthened environmental technological cooperation has been signed[7], while the single EU Member States are collaborating in numerous bilateral projects.[8]

Japan has parallel initiatives with the US and is at the same time strengthening its role in climate cooperation within Asia. In August 2002, the Japanese government announced plans to help other Asian countries reduce greenhouse gases (Jiji Press, Aug. 1st, 2002) and the start of a joint research initiative with seven developing Asian nations aimed at providing technological assistance to the other countries to reduce their GHGs in exchange for CO2 emissions credit (The Daily Yomiuri, Aug. 26th, 2002). In addition, Japan also acts by exporting pollution control technologies and implementing (since 1992) a "Green Aid Plan" to develop research and provide technological assistance for environmental-friendly projects throughout Asia (EIA, 2003).

China has also already signed bilateral agreements with other countries. Apart from its collaboration with the US established in January 2003, China initiated a bilateral cooperation agreement on climate change with Australia in September 2003.[9]

There is therefore an increasing focus on technology as the main way to address the climate change problem, particularly in the long-run. And it is also clear that international cooperation can help develop and disseminate climate-friendly technologies. The recent success in establishing bilateral and multilateral international agreements on technological cooperation may suggest that Barrett's (2001,

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[7] For more information on the EU-China agreement see http://www.delchn.cec.eu.int/en/whatsnew/Pren121103.doc.

[8] See for example http://www.mex.dk/uk/vis_nyhed_uk.asp?id=5834&nyhedsbrev_id=824 for information on a bilateral climate agreement between Denmark and Bulgaria or http://www.climate.org.ua/whatdone/intrn.html for details on the bilateral agreements established with the Ukraine.

[9] For details on the China-US collaboration see http://www.gcrio.org/OnLnDoc/pdf/us-china030116.pdf. The official declaration of the China-Australia cooperation on climate change control is available at http://www.deh.gov.au/minister/env/2003/mr24oct203.html.

2002) and Benedick's (2001) proposal to adopt a technology-based climate protocol might be a better way to address climate change than a protocol in which countries must agree on voluntary GHG emission reductions. However, the recent initiatives briefly outlined in this section are merely indicators of a possible evolution of climate policy, but do not yet support any conclusions in favour of a technology-based climate protocol. This is why we plan to address this issue in this paper and to provide an assessment of this policy proposal, which will be described in greater detail in the next section.

3. Updating, revising or abandoning the Kyoto framework for climate policy?

Numerous recent studies[10] emphasise the fact that, without the US contribution, no effective emission control can be achieved (see Buchner, Carraro and Cersosimo, 2002, for a summary of this literature). In particular, in addition to meaning a straightforward reduction of emission abatement, the US defection has induced a whole chain of reactions. With the largest permit demander dropping out, the demand for GHG emission permits has fallen, which implies a lower than expected carbon price. This lower price reduces the expected costs of complying with the Kyoto Protocol in the remaining Annex B countries, but it also lowers their total amount of emission abatement through leakage effects[11]. Furthermore, the incentives to undertake environmental-friendly R&D and technological innovation also decrease. As a consequence, (i) the environmental effectiveness of the Kyoto Protocol is compromised; (ii) the incentives to abate emissions and invest in climate friendly technologies are substantially lowered in all countries[12], and (iii) in climate negotiations, the bargaining power of permit suppliers, notably Russia, has considerably increased.[13]

[10] See for example Böhringer (2001), Böhringer and Löschel (2001), Buchner, Carraro and Cersosimo (2002), Den Elzen and de Moor (2001a and 2001b), Egenhofer, Hager and Legge (2001), Egenhofer and Legge (2001), Eyckmans, van Regemorter and van Steenberghe (2001), Hagem and Holtsmark (2001), Kopp (2001), Kemfert (2001), and Manne and Richels (2001.

[11] Some studies highlight feedback effects that can mitigate the fall in the permit price. Strategic market behaviours can indeed modify the size of the expected changes in prices and abatement costs. In particular, these changes are much smaller than initially suggested. For example, banking and monopolistic behaviour in the permit market (Manne and Richels, 2001; Den Elzen and de Moor, 2001a and b; Böhringer, 2001) or strategic R&D behaviour (Buchner, Carraro and Cersosimo, 2002) can offset the demand shift and reduce the decline of the permit price consequent to the US withdrawal from the Kyoto Protocol.

[12] The impact on R&D expenditure and consequently on technology and the emission/output ratio of the US decision to withdraw from the Kyoto Protocol has recently been studied by Buchner, Carraro and Cersosimo (2002), where in particular the effect of the lower permit price on the incentives to undertake GHG emission reducing R&D are quantified. The results show the decline of R&D expenditure in all Annex B countries after the US defection from the Kyoto Protocol. Therefore, not only does the US reduce their abatement and R&D efforts, but also those of the other Annex B countries, via spillovers and leakage effects, become lower. As a consequence, the emission/output ratio deteriorates in all Annex B countries (Buchner, Carraro and Cersosimo, 2002).

[13] For example, the outcome of the COP 7 in Marrakech includes considerable concessions to Russia that are evidence of Russia's increased bargaining power. Subsequently, Russia has further exploited its crucial role for

The implications of the US's decisions not to ratify the Kyoto Protocol has led several analysts to explore the possible expediency of other climate regimes. A first option is a climate regime in which the US adopt their own climate policy – possibly in cooperation with some developing countries – whereas the other Annex B countries remain committed to the Kyoto Protocol (Cf. Buchner and Carraro, 2003). A second option is a climate regime in which the Kyoto Protocol is integrated with measures and policies to induce the US to modify their present decision and to ratify the modified Protocol[14]. A third possible regime is based on a completely different approach, in which all countries are required to agree on a climate strategy which is no longer based on the cap and trade of emissions. This new climate regime could be based, for example, on an international carbon tax (Nordhaus, 2001) or on a set of harmonised domestic carbon taxes (Cooper, 1998) or on the adoption of different domestic measures to curb GHG emissions (e.g. in the case of the Global Climate Marshall Fund proposed by Schelling, 2002).[15]

Less radical proposals suggest enhancing the incentives for participation and compliance by focusing on some weaknesses in the Kyoto architecture. For example, some of these proposals investigate a combination of relatively modest short-term goals with more stringent long-term targets, in order to lower the initial burden to commit to the climate agreement. These proposals often include near-term commitments for developing countries[16]. Other proposals aim at reducing the expected costs of the Kyoto Protocol by introducing hybrid policy instruments, e.g. the combination of a quantity instrument (such as emissions trading) with a price instrument (such as a tax or safety valve)[17]. Other proposals suggest adopting a step-by-step approach to climate policy by focusing first on regional agreements (regional "bubbles" to be developed within the Kyoto Protocol) and then moving on to a global agreement[18].

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the coming into force of the Kyoto Protocol by delaying ratification and by negotiating economic transfers from the EU.

[14] One solution often proposed in the literature on international regimes is to link cooperation on climate change control (typically a public good) with cooperation on a club or quasi-club good. This strategy has recently been explored by Tol, Wise and van der Zwaan (2000), and Buchner, Carraro, Cersosimo and Marchiori (2002) which focus on the linkage of climate cooperation with technological cooperation.

[15] For a discussion of different proposals see for example Aldy et al. (2003), Aldy, Barrett and Stavins (2003), Baumert et al (2002), Barrett and Stavins (2004), CNRS/LEPII-EPE et al. (2003) and OECD/IEA (2002).

[16] See for example, Barrett (2001 and 2002); McKibbin and Wilcoxen (1997); McKibbin (2000) and Schmalensee (1998).

[17] See for example, Kopp, Morgenstern, Pizer and Toman (1999); McKibbin and Wilcoxen (1997); McKibbin (2000); and Victor (2001)

[18] See Buchner and Carraro (2004).

More radical proposals are based on the observation, largely shared by climate scientists, that without a real technological breakthrough it will be very difficult to achieve the stabilisation of GHG concentrations. Therefore, an effective climate regime should be based on measures that enhance climate-friendly technological innovation and dissemination and reduce the future costs of greenhouse gas abatement.

The idea that technological cooperation is the appropriate tool to deal with the problem of global warming is not only the basis of the Bush administration's climate policy, but has also been proposed as the framework of a new approach to climate policy at international level by Barrett (2001, 2002) and Benedick (2001). They argue that an international agreement for the development and diffusion of technologies designed to reduce GHG emissions could be a possible approach that countries may decide to adopt to combat climate change[19].

As discussed in section 2, the idea of a technology-based climate protocol is not based on a vacuum. The proliferation of bilateral agreements on technology cooperation – and on climate technology cooperation in particular – would seem to indicate that the proposal for a technology-based climate protocol is worth serious consideration. This type of protocol could be established within the UNFCCC and could be a complement, if not a substitute, of the Kyoto Protocol.

Let us provide a more detailed description of this idea. Barrett (2001, 2002) and Benedick (2001) propose a technology-based international strategy to tackle the incentives to free-ride which usually undermine the possibility of cooperation on emission control. In particular, Barrett (2001, 2002) argues that the Kyoto Protocol provides poor incentives for participation and compliance and tries to solve this problem by suggesting an alternative climate regime, which is based on common incentives for the development and adoption of climate-friendly technologies.

The main elements of this proposal include cooperative funding of basic R&D into energy-saving, climate-friendly technologies on the one hand, and the implementation of various standards directed towards the world-wide adoption and diffusion of new technologies on the other. Common standards for technologies are identified through collaborative research efforts[20], which are financed through the global R&D fund. Every country should be given the option to sign both the standards protocol and the cooperative R&D protocol. Since standards are a public good, no country can be excluded from

[19] See for example Barrett (2001 and 2002), Benedick (2001), Edmonds, Roop and Scott (2000), Edmonds (2001), Flannery (2001), Jacoby (1998). The relative performance of technological innovation with respect to environmental policy tools is discussed in Parry, Pizer and Fischer (2002).

[20] Barrett (2001) cites the example of energy efficiency standards for cars, which could be established requiring e.g. the use of new hybrid engines or fuel cells.

using them. By imposing an open standards protocol, Barrett accounts for competition which induces pull incentives. In addition, the standards protocol is intended to be non-exclusionary in order to encourage the widespread adoption and diffusion of new technologies.

However, to construct a global climate regime which is accepted by all countries, an element of fairness needs to be incorporated, taking into account that the current accumulation of GHG emissions in the atmosphere is basically caused by the industrialised countries. In order to provide incentives for the developing countries to adopt the new standards which will require costly technologies, Barrett suggests making the share of each country's contribution to collaborative funding dependent on its circumstances[21]. In this way, the need for the developing countries to grow is satisfied but – acknowledging that they will probably be the biggest future emitters – they nevertheless take part in a climate regime. In addition, taking the Montreal Protocol as an example, the industrialised countries are made responsible for the financing of technological transfers. Thus, a multilateral fund would ensure that technologies can spread to developing countries. In this way, this approach sets incentives for their participation because – although being bound by the technology standards – they can gain through the diffusion of technologies in their countries which is basically financed by industrialised countries.[22]

Barrett emphasises that the attractiveness of this approach – based on a R&D Protocol with complementary standards protocols – lies in the inclusion of both "push" incentives affecting the supply of R&D, and "pull" incentives aimed at the demand for the benefits of R&D. In contrast, the Kyoto Protocol does not consider the necessity to push R&D, but is based solely on the pull incentives which only work by strong enforcement. Also, by focusing on incentives related to the funding of R&D, preconditions for long-term technical innovation and diffusion are created. Moreover, because emission targets and time tables are not imposed, this technology-based climate regime does not require the enforcement of compliance, but does provide incentives for participation.

Note that the more countries adopt a standard, the more attractive it becomes for other countries to adopt the same standard. Hence, the more countries combat climate change, the greater are the incentives for other countries to follow suit. Therefore, there is no need for strong enforcement and

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[21] In addition, the country's contribution should be contingent on an agreed total expenditure level and the contribution of the other countries (Barrett, 2002). The latter element ensures that the fund becomes larger when countries join the cooperation agreement and smaller when countries withdraw. In this way, an explicit incentive for participation is created and – very important – countries know their commitment costs before signing the agreement.

[22] An additional innovative component of this proposal is an adaptation protocol which explicitly accepts the responsibility of industrialised countries for the current situation with respect to accumulated GHG emissions. Therefore, industrialised countries need to assist developing countries in adapting to the consequences of climate change, which are very likely to be strongest in these countries.

monitoring. Once enough countries adopt the standards, none of them will have an incentive to defect from the agreement.

These considerations are also consistent with the recommendations derived from game theory models that study the effects of cooperation on technological innovation (Cf. Yi, 1997). If technological spillovers are limited, technological cooperation provides a club good, where benefits from cooperation are partly excludable (i.e. free riders achieve a small benefit). In this case, the equilibrium coalition structure often coincides with the grand coalition.[23] By contrast, as shown in Bloch (1997), in the case of public goods, the equilibrium of the coalition game is characterised – in the most favourable cases – by a constellation of small groups of cooperating countries (climate blocs).[24]

Although there is no doubt that the technology-based approach also has a number of weaknesses[25], it does account for some of the crucial requirements needed to make an international climate regime successful: a global scale, strong elements for self-enforcement and a high degree of probability that the international system will support the approach.

However, there is a basic trade-off characterising the implementation of a technology-based climate protocol. On the one hand, technological innovation reduces emissions per unit of output by making climate-friendly technologies available and by reducing their costs. On the other hand, investments in R&D and technological diffusion provide a stimulus to economic growth and therefore increase GHG emissions. This is particularly true in the absence of any emission reduction targets, as proposed in Barrett (2001, 2002). It is therefore crucial to assess whether the adoption of a technology-based climate protocol can actually reduce GHG emissions, i.e. whether the development of new technologies and their dissemination obviates the other collateral effects of the protocol.

Note that other elements of a technology-based protocol need to be carefully verified. For example, are technological spillovers strong enough inside the coalition (the group of cooperating countries) and small enough outside the coalition (towards potential free-riders) to guarantee that all world countries are willing to adopt the protocol? In particular, will developing countries accept to sign such a

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[23] Of course other assumptions are necessary, e.g. that asymmetries are negligible and that the agreement is profitable (see Yi, 1997). However, what matters in our context is the excludability of benefits from cooperation that provides incentives for all or almost all players to join the coalition.

[24] See also Carraro and Marchiori (2003) and the other papers in Carraro (2003).

[25] For example, there are problems in ensuring that the "right/best" standards are chosen and that the adoption of these standards indeed offers every participating country a benefit in excess of the cost. An additional question is who will choose the standards. A further concern is that the system gets locked in to a particular standard which would remove the incentives for further innovation.

protocol? In addition, technology and the skills to adopt it are not evenly distributed across the world. Are these asymmetries strong enough to prevent the emergence of a global agreement?

In order to answer these questions, and to check whether a technology-based climate protocol is actually environmentally effective, we made an applied game-theory analysis of two possible scenarios: the first one is characterised by technological cooperation among the four "traditional" Kyoto countries/regions (USA, Europe, Japan, Former Soviet Union), whereas in the second one all world countries, including developing countries, cooperate on technological innovation and diffusion. For each scenario, we assess the profitability, stability (no free-riding incentives) and environmental effectiveness of technological cooperation.[26]

The aim of our analysis is to verify whether cooperation on technological innovation and diffusion, without any emission reduction commitments, could actually lead to a reduction of global emissions. Were this conjecture true, we could conclude that a technology-based climate agreement would be more efficient than a climate agreement based on emission reduction targets, because the former provides excludable benefits – and thus adequate incentives for participation – while reducing the amount of GHG emissions.

4. Technology-based climate regimes. An assessment

4.1 The modelling framework

In the policy-setting that we are going to analyse, we compare the climate regime which has emerged following the Marrakech negotiations with two scenarios based on technological cooperation. In these scenarios, the group of cooperating countries is set exogenously. In particular, in the first scenario we assume that all Annex B countries – EU, Japan, US, FSU – cooperate on technological innovation and diffusion, without being committed to any emission reduction targets. In the second scenario, we assume global technological cooperation, again without any binding environmental restrictions.

Let us first verify whether these two technological coalitions are self-enforcing, namely profitable and stable. The definitions of profitability and stability have been derived directly from Carraro and Siniscalco (1993) (see also Eyckmans, 2001 and Weyant and Olavson, 1999 for recent applications to climate policy). We say that an agreement is *weakly profitable* if the sum of the individual payoffs of the signatories is larger than the sum of their payoffs when no agreement is signed. In this case, the agreement produces a surplus (overall benefits are larger than costs), but this surplus may not benefit all signatories, i.e. some countries may gain, others may lose. By contrast, an agreement is *strongly profitable,* or simply *profitable,* if the payoff of all signatories is larger when the agreement is signed and implemented than when no agreement is signed. Hence, each single participant obtains a net benefit from the agreement. An agreement is said to be *internally stable* if there is no incentive to free-ride, i.e. the payoff of each signatory is larger than the payoff he/she would obtain by defecting from the group of signatories. Finally, an agreement is *stable* if there is no incentive to free ride and no incentive to join the group of signatories, i.e. the payoff to those countries that are not signatories is larger than the one they would receive by signing the agreement.

The analysis of the profitability and stability of our two technology-based climate agreements (the Annex B one and the global one) is based on optimisation runs obtained using the FEEM-RICE model. This version of Nordhaus and Yang's (1996) RICE model takes explicitly into account endogenous and induced technical change. In particular, as previously indicated, technical change performs a twofold role: on the one hand, via increasing returns to scale, it yields endogenous growth; on the other hand, by affecting the emission/output ratio, it accounts for the adoption of cleaner and energy-saving technologies. A brief description is contained in the Appendix.

In the model, six countries/regions – United States (US), Europe (EU), Japan (JPN), Former Soviet Union (FSU), China (CHN) and Rest of the World (ROW) – optimally set the inter-temporal values of three strategic variables: investments, R&D expenditure and abatement rates. Given the interdependency of each country's decision, the equilibrium value of these variables is the solution to a dynamic open-loop Nash game between the six players.

In our policy setting, countries are supposed to cooperate on technological innovation and diffusion and thus choose their R&D expenditure in order to maximise the coalition's joint welfare function. In addition, the optimal value of R&D expenditure depends, among other things, upon the international technological spillovers and the coalition's (internal) technological spillovers. As stated above, countries are not committed to reduce their own GHG emissions. Therefore, they implement their domestic welfare maximising abatement rate. The same holds for the third strategic variable – investment – which is again set by all countries in order to maximise domestic welfare.

By contrast, in our benchmark policy setting in which the Annex B_{US} countries (EU, Japan and Russia) are supposed to comply with the Kyoto Protocol, their abatement rates are set so as to achieve

[26] Please note that the results shown below must be interpreted as an application of a game-theory model designed to identify incentive mechanisms and the economic factors behind them, rather than to provide realistic figures on the outcomes of future policy scenarios.

the Kyoto targets, whereas the US, CHN and ROW implement their domestic welfare maximising abatement rate[27]. As for the other two strategic variables, they are set by all countries in a way that maximises their own domestic welfare.

In order to give technological cooperation the highest probability of being successful, we assume that climate policy is undertaken through domestic policy and measures (no flexibility mechanisms). Recent studies have shown that R&D and flexibility mechanisms are strategic substitutes[28]. As a consequence, countries have the largest incentive to profit from the benefits yielded by R&D cooperation when flexibility mechanisms are not allowed for.

In the FEEM-RICE model, technical change is induced by knowledge accumulation, which is the sum of past R&D expenditures. We assume that part of the technological benefits yielded by this knowledge accumulation are a global public good, whereas part of them are a club good that can be appropriated only by the R&D coalition members. Therefore, R&D cooperation is assumed to be an imperfect club good. In the model, the parameter β quantifies the increased share of world knowledge that can be appropriated by countries belonging to the R&D coalition (see the Appendix). This parameter is equivalent to the "differential technological spillover" or "coalition information exchange coefficient" in the theoretical model by Carraro and Siniscalco (1995, 1997). The FEEM-RICE model is thus characterised by the inclusion of two types of spillovers and related parameterisation: spillovers – parameterised by ε – which are appropriated by all countries; and spillovers – parameterised by β – which are beneficial only to coalition members.

The main characteristics of the FEEM-RICE model used in this paper can be summarised as follows: (i) R&D expenditure becomes one of countries' strategic variables; (ii) accumulated knowledge (the sum of past R&D expenditures) affects both economic growth and the emission/output ratio; and (iii) the higher the coalition-internal spillovers, the more countries sign the treaty, and the more profitable technological cooperation becomes.

[27] When deriving the results for the actual Kyoto coalition consisting of EU, JPN and FSU, we adopt the so-called "Kyoto forever" scenario which is used in most of the literature on the economic costs of climate policy. See e.g., Buonanno, Carraro and Galeotti (2002); Manne and Richels (1999); and Chapter 8 of IPCC (2001). In particular, we assume that countries which have agreed with the Marrakech negotiations commit themselves to meeting the existing Kyoto constraints from 2012 onward, given that no emission targets beyond 2012 are yet defined.

[28] Buonanno, Carraro and Galeotti (2002) show that an international trading system, by lowering the cost of complying with the Kyoto targets, also lowers the incentives to undertake environment-friendly R&D. Therefore, at the equilibrium, R&D expenditure is lower in all countries that benefit from emission trading. R&D and emission trading are thus strategic substitutes.

Therefore, the coalition-internal spillovers β play a crucial role in determining the effectiveness of technological cooperation for the single countries. As a consequence, the next step will be to assess the interdependence between the value of β and the environmental effectiveness of the technology-based climate agreement.

4.2 An applied game-theory analysis of two technology-based climate regimes

In this section we proceed in a counterfactual manner. First, we assume that only the four "traditional" Kyoto regions (USA, Europe, Japan, Former Soviet Union) decide to replace environmental cooperation by technological cooperation. The other two regions – China and Rest of the World – are excluded for the moment from technological cooperation. Second, we evaluate a scenario in which a global R&D coalition forms, namely all world countries cooperate on technological innovation and diffusion. Finally, we compare the empirical results obtained for these two scenarios with those in the case of a climate coalition where the EU, JPN and FSU are committed to achieving the Kyoto targets, whereas the other countries free-ride.

Let us consider first the profitability and stability of climate agreements based on technological cooperation. Our results can be summarised as follows. *Both the coalition in which Annex B countries/regions cooperate on technological innovation and diffusion and the coalition in which all world countries regions cooperate on technological innovation and diffusion are profitable and internally stable for values of b ³ 0.2*. Therefore, as soon as the excludable benefits arising from technological cooperation become relevant ($\beta \geq 0.2$, i.e. benefits for co-operators are 20% higher than benefits accruing to free-riders), all countries find it profitable to cooperate. In addition, there is no incentive to free-ride on technological cooperation. The reason lies in the availability of economic benefits (parameterised by β) that can be appropriated only by coalition members (this also incorporates Barrett's argument about technological standards).

The crucial issue is therefore the environmental effectiveness of a coalition in which member countries cooperate only on technological development and its diffusion. Our results are summarised in Tables 1 and 2. The first column shows different values of the parameter β. The second column contains the change of global emissions in the case of a technology-based protocol versus global emissions in the case of an emission target protocol (i.e. our benchmark case in which the EU, JPN and FSU meet their Kyoto targets, the other countries free-ride and no technological cooperation is implemented). The third column contains the change of the emission/output ratio induced by R&D cooperation (again with respect to the same benchmark). While the second and the third columns show the results in the first commitment period, the fourth and the fifth columns show what could happen in the medium term (the time horizon is 2050).

Table 1 illustrates that both global emissions and the emission/output ratio increase in the case of a technology-based protocol among Annex B countries. Note that there are no cases in which technological cooperation can induce a reduction of global emissions and/or of the emission/output ratio.[29]

Table 1. Environmental effectiveness of a technology-based protocol among Annex B countries

	2010		2050	
b	Percentage change of global emissions	Percentage change of aggregate emission/output ratio	Percentage change of global emissions	Percentage change of aggregate emission/output ratio
0.10	+ 12.96%	+ 13.09%	+ 49.18%	+ 48.98%
0.20	+ 12.97%	+ 12.99%	+ 48.28%	+ 47.99%
0.33	+ 12.97%	+ 12.88%	+ 48.87%	+ 48.42%
0.66	+ 13.01%	+ 12.68%	+ 48.60%	+ 47.83%
1.00	+ 13.07%	+ 12.53%	+ 48.46%	+ 47.40%
1.50	+ 13.13%	+ 12.35%	+ 48.18%	+ 46.88%

Note: β is the differential technological spillover or coalition information exchange coefficient. Changes of emissions are computed with respect to the benchmark case in which the EU, JPN and FSU meet their Kyoto targets, the other countries/regions do not cooperate on emission control and no technological cooperation is implemented.

The intuition behind this result is as follows. As a consequence of the intensified R&D efforts, production increases. This raises the emissions of the Annex B countries that cooperate on R&D. Emissions per unit of output also increase, because the overall impact of accumulated R&D expenditure on economic growth (the endogenous growth effect) is larger than the impact of accumulated R&D on emission abatement (the induced technical change effect).

[29] At least to the extent that the FEEM-RICE model can adequately capture the dynamics of induced technical change.

[30] The reason for this drastic increase is that we compare a situation in which the European Union, Japan and Russia are committed to strict, binding emission reduction targets (due to our use of the "Kyoto forever" assumption) to a situation in which there are no mandatory emission reduction targets.

These negative conclusions on the environmental effectiveness of an international climate protocol based only on technological cooperation are even stronger when looking at the situation in 2050. Both absolute emissions and the aggregate emissions/output ratio increase by almost 50% with respect to the current situation in which only the EU, Japan and FSU are committed to comply with the Kyoto targets[31].

The reason for this difference is that the effects of the increased investments in R&D can be seen more clearly in 2050 than in 2010. An important additional reason is that in the medium term technological spillovers have a strong effect on the growth rate of China and ROW (which do not participate in the technological agreement and therefore get part of the technological benefits – through the global spillovers ε – at no cost).

Can more satisfactory conclusions be achieved if a global technology-based protocol – which would involve all world countries – is established? Again, even though global cooperation increases the economic benefits and the environmental effectiveness of the agreement, total emissions in the technology-based protocol increase with respect to total emissions in the benchmark case (see Table 2). The increase of emissions is smaller when all world regions cooperate to develop and diffuse climate-friendly technologies than in the case in which developing countries free ride. However, the hypothesis that a policy which fosters technological cooperation can also induce less GHG emissions is not supported by our results.

Also note that, at least in the short term, higher internal R&D spillovers lead to higher overall emissions and higher emissions per unit of output. Again, the reason is that an enhanced technological cooperation pushes economic growth and increases welfare, but also increases emissions. This latter increase is only partly mitigated by the participation of CHN and ROW, which help reduce the emission-output ratio, thus lowering the global increase of emissions (see Table 2).

Even though the rate of growth of emissions per unit of output becomes smaller as a consequence of increased R&D efforts – which demonstrates that technological cooperation actually induces an environmental improvement of production technologies – our analysis does not seem to support the idea that a technology-based climate protocol can actually reduce total GHG emissions.

[31] The reason for this drastic increase is that we compare a situation in which the European Union, Japan and Russia are committed to strict, binding emission reduction targets (due to our use of the "Kyoto forever" assumption) to a situation in which there are no mandatory emission reduction targets.

Table 2. Environmental effectiveness of a global technology-based climate protocol

	2010		2050	
b	**Percentage change of global emissions**	**Percentage change of aggregate emission/output ratio**	**Percentage change of global emissions**	**Percentage change of aggregate emission/output ratio**
0.10	+ 2.15%	+ 1.70%	+ 9.65%	+ 8.79%
0.20	+ 2.19%	+ 1.67%	+ 9.73%	+ 8.85%
0.33	+ 2.24%	+ 1.64%	+ 10.14%	+ 9.23%
0.66	+ 2.30%	+ 1.54%	+ 9.48%	+ 8.55%
1.00	+ 2.35%	+ 1.44%	+ 10.06%	+ 8.95%
1.50	+ 2.40%	+ 1.36%	+ 9.78%	+ 8.57%

Note: β is the differential technological spillover or coalition information exchange coefficient. Changes of emissions are computed with respect to the benchmark case in which the EU, JPN and FSU meet their Kyoto targets, the other countries do not cooperate on emission control and no technological cooperation is implemented.

Therefore, the tentative conclusion is that technological cooperation cannot replace environmental cooperation. Within the limits of the FEEM-RICE, our game theory analysis suggests that technological cooperation increases R&D, growth and welfare, but also emissions. As a consequence, some environmental policy measures, to be coupled with technological cooperation, seem to be necessary to achieve an environmentally satisfactory regime. If appropriately designed, these environmental policy measures could also provide additional incentives to invest in climate-friendly technological change[32].

[32] Some results obtained in Buchner, Carraro, Cersosimo and Marchiori (2002) provide support to this conclusion. Indeed, we found that total emissions when all or part of the Annex B countries adopt technological cooperation and environmental policy measures to achieve the Kyoto targets, are smaller than total emissions when international cooperation concerns only technological innovation and diffusion. Moreover, with both technological and climate cooperation, global emissions are smaller than the global Kyoto target itself.

5. Conclusions

The analysis of this paper has been motivated by the increasing number of bilateral deals on technological cooperation that have emerged following the US withdrawal from the Kyoto Protocol. In addition, and independently of this flow of initiatives on technological cooperation, the proposal of a technology-based climate protocol has been debated from a theoretical perspective and its properties in terms of participation incentives have been highlighted by several authors (e.g. Barrett, 2001, 2002).

As a consequence, the main objective of this paper was to verify, using an applied game theory approach, whether a climate regime based on cooperation on technological innovation and diffusion, without any binding abatement commitments, could be self-enforcing and yield lower total GHG emissions than other regimes. Were this conjecture true, a technology-based climate agreement could replace agreements focused on emission abatement targets, because it would provide both stronger incentives to participate and a better performance in terms of environmental effectiveness.

Unfortunately, the scenarios that have been analysed in this paper do not support the above conjecture. Although technological cooperation without emission abatement commitments increases economic growth and welfare, this strategy does not lower global GHG emissions. Therefore, notwithstanding the positive theoretical foundations, the replacement of the Kyoto Protocol by a technology-based protocol does not seem to be environmentally effective. Some emission reduction policies are likely to be necessary – in addition to technological cooperation – to provide a satisfactory degree of environmental effectiveness.

Of course, the conclusions of this study need to be tested using other models and other specifications of technical change. This would provide additional evidence on the properties of a technology-based climate protocol and would enable us to draw sounder conclusions. At the same time, the conclusion of this study should not be taken as a strong rejection of a technology-based protocol. Its solid theoretical properties, the positive signs expressed by the industry towards a technology-based regime and the increased amount of bilateral deals signed among different countries around the world suggest that technological cooperation would be part of a successful strategy to control climate change. Technological cooperation should be considered as an element of a more comprehensive policy strategy through which emission reductions are actually achieved at the global level – possibly in a cost-effective way and with the contribution of most of the world's countries.

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Appendix. The FEEM-RICE Model

The FEEM-RICE model is an extension of Nordhaus and Yang's (1996) regional RICE model of integrated assessment, which is one of the most popular and manageable integrated assessment tools for the study of climate change (see, for instance, Eyckmans and Tulkens, 2001). It is basically a single sector optimal growth model which has been extended to incorporate the interaction between economic activities and climate. One such model has been developed for each macro region into which the world is divided (USA, Japan, Europe, China, Former Soviet Union, and Rest of the World).

Within each region a central planner chooses the optimal paths of fixed investment and emission abatement that maximise the present value of per capita consumption. Output (net of climate change) is used for investment and consumption and is produced according to constant returns Cobb-Douglas technology, which combines the inputs from capital and labour with the level of technology. Population (taken to be equal to full employment) and technology levels grow over time in an exogenous fashion, whereas capital accumulation is governed by the optimal rate of investment. There is a wedge between outputgross and net of climate change effects, the size of which is dependent upon the amount of abatement (rate of emission reduction) as well as the change in global temperature. The model is completed by three equations representing emissions (which are related to output and abatement), carbon cycle (which relates concentrations to emissions), and climate module (which relates the change in temperature relative to 1990 levels to carbon concentrations) respectively.

In our extension of the model, technical change is no longer exogenous. Instead, the issue of endogenous technical change is tackled by following the ideas contained in both Nordhaus (1999) and Goulder and Mathai (2000) and accordingly modifying Nordhaus and Yang's (1996) RICE model. Doing so requires the input of a number of additional parameters, some of which have been estimated using information provided by Coe and Helpman (1995), while the remaining parameters were calibrated so as to reproduce the business-as-usual scenario generated by the RICE model with exogenous technical change.

In particular, the following factors are included: first, endogenous technical change affecting factor productivity is introduced. This is done by adding the stock of knowledge in each production function and by relating the stock of knowledge to R&D investments. Second, induced technical change is introduced, by allowing the stock of knowledge to affect the emission-output ratio as well. Finally, international technological spillovers are also accounted for in the model.

Within each version of the model, countries play a non-cooperative Nash game in a dynamic setting, which yields an Open Loop Nash equilibrium (see Eyckmans and Tulkens, 2001, for an explicit derivation of first order conditions of the optimum problem). This is a situation in which, in each region, the planner maximises social welfare subject to the individual resource and capital constraints and the climate module, given the emission and investment strategies (in the base case) and the R&D expenditure strategy (in the endogenous technological change case) of all other players.

The Standard Model without Induced Technical Change

As previously mentioned, it is assumed for the purpose of this model that innovation is brought about by R&D spending which contributes to the accumulation of the stock of existing knowledge. Following an approach pioneered by Griliches (1979, 1984), it is assumed that the stock of knowledge is a factor of production, which therefore enhances the rate of productivity (see also the discussion in Weyant, 1997; Weyant and Olavson, 1999). In this formulation, R&D efforts prompt non-environmental technical progress, but with different modes and elasticities. More precisely, the RICE production function output is modified as follows:

$$Q(n,t) = A(n,t) K_R(n,t)^{b_n} [L(n,t)^g K_F(n,t)^{1-g}] \tag{1}$$

where Q is output (gross of climate change effects), A the exogenously given level of technology and K_R, L, and K_F are respectively the inputs from knowledge capital, labour, and physical capital.
In (1), the stock of knowledge has a region-specific output elasticity equal to b_n *(n=1,…6)*. It should be noted that, as long as this coefficient is positive, the output production process is characterised by increasing returns to scale, in line with current theories of endogenous growth. This implicitly assumes the existence of cross-sectoral technological spillovers within each country (Romer, 1990). In addition, it should be noted that while allowing for R&D-driven technological progress, we continue to consider the possibility that technical improvements can also be determined exogenously (the path of A is the same as that specified in the original RICE model). The stock accumulates in the usual fashion:

$$K_R(n,t+1) = R\&D(n,t) + (1-d_R) K_R(n,t) \tag{2}$$

where *R&D* is the expenditure in Research and Development and d_R is the rate of knowledge depreciation. Finally, it is recognised that some resources are absorbed by R&D spending. That is:

$$Y(n,t) = C(n,t) + I(n,t) + R\&D(n,t) \tag{3}$$

where Y is net output (net of climate change effects as specified in the RICE model), C is consumption and I gross fixed capital formation.

At this stage the model maintains the same emissions function as Nordhaus' RICE model which will be modified in the next section:

$$E(n,t) = s\,(n,t)[1 - m(n,t)]Q(n,t) \tag{4}$$

where s can be loosely defined as the emissions-output ratio, E stands for emissions and m for the rate of abatement effort. The policy variables included in the model are rates of fixed investment and of emission abatement. For the other variables, the model specifies a time path of exogenously given values. Interestingly, this is also the case for technology level A and of the emissions-output ratio s. Thus, the model presented so far assumes no induced technical change, i.e. an exogenous environmental technical change, and a formulation of productivity that evolves both exogenously and endogenously. In the model, investment fosters economic growth (thereby driving up emissions) while abatement is the only policy variable used for reducing emissions.

Induced Technical Change

In the second step of our model formulation, endogenous environmental technical change is accounted for. It is assumed that the stock of knowledge – which in the previous formulation was only a factor of production - also serves the purpose of reducing, *ceteris paribus*, the level of carbon emissions. Thus, in the second formulation, R&D efforts prompt both environmental and non-environmental technical progress, although with different modes and elasticities.[33] More precisely, the RICE emission-output relationship is modified as follows:

$$E(n,t) = [s_n + c_n \exp(-a_n K_R(n,t))][1 - m(n,t)]Q(n,t) \tag{4'}$$

In (4'), knowledge reduces the emissions-output ratio with an elasticity of a_n, which is also region-specific; the parameter c_n is a scaling coefficient, whereas s_n is the value to which the emission-output ratio tends asymptotically as the stock of knowledge increases without limit. In this formulation, R&D

[33] Obviously, we could have introduced two different types of R&D efforts, respectively contributing to the growth of an environmental knowledge stock and a production knowledge stock. Such undertaking however is made difficult by the need to specify variables and calibrate parameters for which there is no immediately available and sound information in current literature.

contributes to output productivity on the one hand, and affects the emission-output ratio - and therefore the overall level of pollution emissions - on the other.

Knowledge Spillovers

Previous formulations do not include the effect of potential spillovers produced by knowledge, and therefore ignore the fact that both technologies and organisational structures disseminate internationally. Modern economies are linked by vast and continually expanding flows of trade, investment, people and ideas. The technologies and choices of one region are and will inevitably be affected by developments in other regions.

Following the work of Weyant and Olavson (1999), who suggest that the definition of spillovers in an induced technical change context be kept plain and simple (in the light of a currently incomplete understanding of the problem) , disembodied, or knowledge spillovers are modelled (see Romer, 1990). They refer to the R&D carried out and paid for by one party that produces benefits to other parties which then have better or more inputs than before or can somehow benefit from R&D carried out elsewhere. Therefore, in order to capture international spillovers of knowledge, the stock of world knowledge is introduced in the third version of the FEEM-RICE model, both in the production function and in the emission-output ratio equation. Equations (1) and (4') are thus revised as follows:

$$Q(n,t) = A(n,t)K_R(n,t)^{b_n} WK_R(n,t)^{e_n} [L(n,t)^g \, K_F(n,t)^{1-g}] \qquad (1')$$

and:

$$E(n,t) = [\sigma_n + \chi_n \, exp(-\alpha_n K_R(n,t) - \theta_n WK_R(n,t))][1 - \mu(n,t)]Q(n,t) \qquad (4'')$$

where the stock of world knowledge:

$$WK_R(j,t) = b \sum_{\substack{i \in coal \\ i \neq j}} K_R(i,t) + \sum_{i \notin coal} K_R(i,t) \qquad (5)$$

is defined in such a way as not to include a country's own stock and where b is the coalition information exchange coefficient ($b > 0$).