A joint Initiative of Ludwig-Maximilians-Universität and Ifo Institute for Economic Research

CESifo Working Papers

BACK TO KYOTO? US PARTICIPATION AND THE LINKAGE BETWEEN R&D AND CLIMATE COOPERATION

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CESifo Working Paper No. 688 (8)

March 2002

Category 8: Resources and Environment

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ISSN 1617-9595

* The authors are grateful to Marni Wood and to all members of FEEM Climate Modelling and Policy Unit for suggestions and remarks. The usual disclaimer applies.

CESifo *Working Paper No. 688*
March 2002

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Abstract

The US decision not to ratify the Kyoto Protocol and the recent outcomes of the Bonn and Marrakech Conferences of the Parties drastically reduces the effectiveness of the Kyoto Protocol in controlling GHG emissions. The reason is not only the reduced emission abatement in the US, but also the spillover effects on technology and countries' relative bargaining power induced by the US decision. Therefore, it is crucial to analyse whether an incentive strategy exists that could induce the US to revise their decision and to comply with the Kyoto commitments. One solution, occasionally proposed in the literature and in actual policymaking, is to link negotiations on climate change control with decisions concerning international R&D cooperation. This paper explores this idea by analysing on the one hand the incentives for EU, Japan and Russia to adopt this strategy, and on the other hand the incentives for the US to join a coalition which cooperates both on climate change control and on technological innovation. The extended regime in which cooperation takes place on both dimensions (GHG emissions and R&D) will be examined from the view point of countries' profitability and free-riding incentives. Finally, after having assessed the effectiveness and credibility of the issue linkage strategy, we explore the economic and environmental benefits of a new, recently proposed regime, which aims at achieving GHG emission control by enhancing cooperation on technological innovation and diffusion (without targets on emissions).

JEL Classification: C7, H0, H4, O3.

Keywords: agreements, climate, incentives, negotiations, policy, technological change.

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Back to Kyoto? US Participation and the Linkage between R&D and Climate Cooperation

1. Introduction

In the last few decades, international and global environmental issues have become an important concern of the international community. Among the variety of environmental challenges, climate change is considered as one of the most serious threats to the sustainability of the world socio-economic system. In order to tackle global environmental problems in the most effective way, as many countries as possible -- or at least a number of countries which account for a large share of total emissions -- have to take action. However, no supra-national authority capable of enforcing environmental policies and regulations yet exists. Therefore, environmental protection can only be achieved via international agreements among sovereign countries.

The international political response to climate change was introduced within the United Nations Framework Convention on Climate Change (UNFCCC) which was adopted in 1992. In 1997, the UNFCCC agreed to the Kyoto Protocol, setting for the first time binding emissions reduction targets for industrialised countries. In particular, by 2012 the world wide greenhouse gas emissions should decline by an average 5,2% below their 1990 levels. The Kyoto Protocol represents remarkable progress in the history of international environmental agreements and its implementation could lay the basis for effective global action. However, the Kyoto Protocol determined only the targets, methods and timetables for global action, while the definition of specific rules and operational details was postponed to later meetings. This is one of the reasons why the Protocol has not yet entered into force: many countries signed the Protocol, but few actually ratified it[1].

After the political deal concluded in Bonn, an agreement on the outstanding "technical" issues could be reached in Marrakech within the 7th Conference to the Parties. The majority of the missing details relating to the structure of the Kyoto Protocol have been negotiated, thereby clearing the way for the Protocol's "timely" entry into force. After heavy concessions had been made to some of the countries (above all to Russia), an agreement on the operational details for commitments on reducing emissions of greenhouse gases (GHGs) has been finalised. Therefore, the road for the Kyoto Protocol ratification and implementation seems to be paved.

Notwithstanding this success, international climate policy suffers a major problem: the world largest economy, the United States, does not wish to play a part in the Kyoto/Bonn/Marrakech Protocol. Although

[1] The ratification status of the Kyoto Protocol as of March 5th, 2002: 84 countries signed the Kyoto Protocol (and accepted it in this way officially), but only 48 countries (mainly small island states) ratified it. For recent updates see http://www.unfccc.de/resource/kpstats.pdf.

being a party to the UNFCCC, in March 2001 the US President George W. Bush announced the US withdrawal from the Kyoto Protocol due to the harm that this climate agreement would incur on the US economy. After this official statement, the US did not take part in the subsequent negotiations on the Protocol.

A recent strand of literature (see Buchner, Carraro and Cersosimo, 2001, for a summary) analyses the consequences of the US withdrawal from the Kyoto Protocol. Three main effects are highlighted:

- The US rejection and the new provisions included in the Marrakech agreement imply a strong decline in the environmental effectiveness of the Kyoto Protocol.
- The US defection induces a decreasing demand for emission permits and consequently a decline in the permit price, thus reducing the incentives to abate emissions and invest in climate friendly technologies in all countries.[2]
- The smaller permit price after the US defection reduces Russia's benefits from participating in the Kyoto agreement. This provides additional incentives for Russia to use its increased bargaining power in climate negotiations.[3]

Therefore, the US withdrawal from the Kyoto Protocol induces serious environmental and economic problems, ranging from a deterioration of the environmental effectiveness of the Protocol to the increase in Russia's bargaining power. As a consequence, the need to involve the US again in the international efforts to combat climate change is strengthened.

As shown by these recent events, broad participation on environmental issues is hard to achieve. This conclusion is also supported by theoretical findings. There are probably two main reasons which explain the difficulty for countries to sign an environmental agreement. The first is the large economic and environmental asymmetries among world regions. These structural differences induce a difficulty to share the burden of emission reductions in a way that makes it convenient for most countries to sign the agreement.

The second reason is the intrinsic instability of environmental negotiations: even in the absence of asymmetries, some countries may prefer to free-ride, i.e. to profit from the cleaner environment provided by signatory countries, without paying the costs (because environmental benefits are not excludable: climate change control is a global public good).

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[2] 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, 2001; Böhringer, 2001b) or strategic R&D behaviour (Buchner, Carraro and Cersosimo, 2001) can offset the demand shift and reduce the decline of the permit price consequent to the US withdrawal from the Kyoto Protocol.

[3] A precondition for the Kyoto Protocol to become 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 Russia has thus become crucial. The recent outcome of the COP 7 in Marrakech includes considerable concessions to Russia and thereby confirms Russia's increased bargaining power.

For these reasons, an important strand of literature is focused on policy strategies that can increase environmental cooperation (see Carraro and Siniscalco, 2002; Carraro and Galeotti, 2002 for recent surveys). The main economic mechanisms that have been proposed to induce more countries to ratify the Kyoto Protocol are transfers and "issue linkage", even though negotiation rules and treaty design can also be used to enlarge the equilibrium size of environmental coalitions (Carraro, 2000).

It is quite natural to propose transfers to compensate those countries which may lose out by signing the environmental agreement. The idea is that a redistribution mechanism among signatories, from gainers to losers, may provide the basic requirement for a self-enforcing agreement to exist: the profitability of the agreement for all countries. Transfers also play a major role with respect to the stability issue. The possibility of using self-financed transfers to offset free-riding incentives, i.e. to stabilise environmental agreements, is analysed in Carraro and Siniscalco (1993), Hoel (1994), who show that transfers may be successful only if associated with a certain degree of commitment. When countries are symmetric, only if a group of countries is committed to cooperation, another group of uncommitted countries can be induced to sign the agreement by a system of transfers.[4]

However, transfers are hardly ever adopted in actual climate negotiations. One reason is that payments must be provided in advance and this can induce strategic behaviour both in signatories and non-signatories countries. In other words, cooperating players could under-estimate their initial gains in order to decrease the amount of transfers they must provide; while on the other hand, free-riders could over-estimate their loss in order to obtain a larger amount of financial transfers.

For these reasons, both the economic and the political science literature on international environmental agreements propose an alternative approach to increase the number of signatories of an international agreement. The alternative approach, called *issue linkage*, is based on the idea that countries may have incentives to free ride on a global public good, but these incentives become much smaller if negotiations on the global public good are linked with negotiations on another economic issue (typically a club good whose benefits cannot be reaped by free-riders).

Therefore, issue linkage consists in designing a negotiation framework in which countries do not negotiate on just one issue (e.g. the environmental issue), but negotiate on two joint issues (e.g. the environmental one and another interrelated economic issue).

Pioneering contributions on issue linkage are those by Tollison and Willett (1979), Haas (1980) and Sebenius (1983). They propose this mechanism to promote cooperation not only on environmental matters, but also on other issues, e.g. security and international finance. They also emphasise the increase in transaction costs that can result from the use of issue linkage.

[4] This constraint is weaker in the case of asymmetric countries (see Botteon and Carraro, 1997a).

Issue linkage was introduced in the economic literature on international environmental cooperation by Folmer et al. (1993) and by Cesar and De Zeeuw (1996) to solve the problem of asymmetries among countries. The intuition is simple: if some countries gain on a given issue and other countries gain on a second one, by linking the two issues we can obtain a profitable agreement for all countries.

However, issue linkage can also be used to mitigate the problem of free-riding. To do this, negotiations that are affected by this problem, i.e. negotiations concerning public goods, must be linked with negotiations on club or quasi-club goods. The intuition is that the incentives to free-ride on the non-excludable benefits of the public good can be offset by the incentives to appropriate the excludable benefits given by jointly providing a club good.

Barrett (1995, 1997), for example, proposes to link environmental protection to negotiations on trade liberalisation. In this way, potential free-riders are deterred with threats of trade sanctions. In Carraro and Siniscalco (1995, 1997) and Katsoulacos (1997), environmental cooperation is linked to cooperation in Research and Development. If a country does not cooperate on the control of the environment, it looses the benefits of technological cooperation. Mohr (1995) and Mohr et al. (1998) propose to link climate negotiations to international debt swaps. All these contributions have shown, from a theoretical point of view, the effectiveness of issue linkage in increasing the equilibrium number of cooperators on the provision of the public good.

The goal of this paper is to analyse whether the linkage of cooperation on climate change control with cooperation on technological innovation and diffusion can help by moving the US back to Kyoto. Namely, whether the possibility of getting R&D cooperation benefits, which can be obtained only through cooperation on climate change control, constitutes a sufficient incentive for the US to comply with the Kyoto targets.

This paper explores this idea by analysing on the one hand the incentives for the European Union (EU), Japan (JPN) and Russia (FSU) to adopt the issue linkage strategy, and on the other hand the incentives for the US to join a coalition which cooperates both on GHG emission control and on R&D investment and technological diffusion. The extended regime in which cooperation takes place on both dimensions (climate and R&D) will be examined from the view point of countries' profitability and free-riding incentives.

The structure of the paper is as follows. In section 2, we provide some evidence of the small environmental effectiveness of the Bonn/Marrakech agreement without the US. We also discuss some feedback effects arising as a consequence of the US withdrawal from the Kyoto agreement. In section 3, we identify the theoretical conditions for issue linkage to induce the US to move back to Kyoto. Then, in section 4, by using the RICE model with endogenous and induced technical change -- the so-called ETC-RICE model -- we verify whether these conditions are actually met in reality (as far as reality is represented by our model).

Our results do not seem to support the linkage between climate and R&D cooperation as an effective strategy to induce the US to accept and ratify the Kyoto Protocol. Therefore, we explore another climate regime, recently proposed by Barrett (2001), in which countries cooperate only on technological innovation and diffusion, without any binding abatement commitment. Using again the ETC-RICE model, in section 5 we assess the environmental and economic benefits of this proposal. A concluding section summarises the main achievements of this paper and describes future research directions.

2. Environmental and economic benefits of US cooperation

As already outlined in the Introduction, the US decision to withdraw from the Kyoto Protocol has three important consequences[5]: (i) it reduces the environmental effectiveness of the Protocol; (ii) it lowers the incentives to undertake energy-saving R&D, and (iii) it increases the bargaining power of permit suppliers, Russia in particular.

Let us provide some empirical evidence to support the above conclusions. The US withdrawal from Kyoto reduces the demand for GHG emission permits. Therefore, the equilibrium price in the permit market is lower. This lower price reduces the 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. In addition, the incentives to undertake environmental-friendly R&D and technological innovation are lowered.

The effects of the US decision to withdraw from the Kyoto Protocol on the price of GHG emission permits and on the related compliance costs are shown in Table 1, which summarises the results obtained in several recent studies. Table 1 shows that the aforementioned effects on the permit price and on compliance costs can be quite relevant.

Table 2 summarises recent empirical evidence on the environmental effectiveness of the Kyoto/Bonn Protocol after the US decision not to comply with the targets set in Kyoto. It is clear that the emission abatement achieved by the remaining Annex B countries is much lower than the –5,2% agreed upon in Kyoto. The reason for this result is obvious. The US represent the world's largest economy. Its CO2 emissions made up about 32% of the industrialised countries' emissions in 1990 and are thus responsible for a large share of global GHG emissions. In addition, the Kyoto Protocol imposes a particularly stringent emission target on the US. In order to meet its Kyoto target of -7% -- which is higher than the average -5,2% for industrialised countries as a whole -- the US would have to reduce their GHG emissions by 25-30% in 2010. Therefore, the US defection from the Kyoto agreement implies the impossibility in achieving the 5,2% global target.

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

Table 1. Implications of the U.S. withdrawal from the Kyoto Protocol. Changes of permit price and compliance costs in 2010.

	International permit price*			Total compliance costs*		
	Kyoto Protocol	**KP plus sinks**	**KP plus other provisions**	**Kyoto Protocol**	**KP plus sinks**	**KP plus other provisions**
Hagem and Holtsmark (2001)	- 66.7%	-	Ceilings: + 6.7%	Almost no cost	-	-
Kemfert (2001)	- 84.6%	-	-	Almost no cost	-	-
Eyckmans et al. (2001)	- 54.3%	- 54.1% (with CPR)	CPR + ceilings: - 37.3%	Almost no cost	- 27.6% (with CPR)	CPR + ceilings: + 31%
Den Elzen and Manders (2001)	- 63.2%	- 73%	-	- 87.5%	- 92.5%	-
Böhringer (2001)	- 88.5%	- 100%	-	- 96.7%	- 100%	With 60% banking: – 50%
Manne and Richels (2001)**	-	-	Sinks + banking: - 12.7%	-	-	Sinks + banking: small variat.
Den Elzen and de Moor (2001b)	- 55.6%	- 75%	With 50% banking: - 44.4%	- 81.6%	- 89.5%	With 50% banking: - 72.1%
Böhringer and Löschel (2001)	-	Perfect competition: -100%; Monopolistic supply: - 37.3%	-	-	Perfect competition: - 100%; Monopolistic supply: - 72.3%	-
Buchner et al. (2001)	- 34.9%	-	-	- 66.76%	-	-
Den Elzen and de Moor (2002)	-55.3%***	-	Marrakech: - 76.3%	- 81.6%	-	Marrakech: - 92.1%

* Percentage changes are computed with respect to the values of permit price and compliance costs in the case in which the US is assumed to comply with the Kyoto Protocol.

** This paper assumes that the US will start complying with its Kyoto emissions constraint in 2020.

*** This result is an updated and corrected version of the analysis in Den Elzen and de Moor (2001b).

Table 2. Implications of the U.S. withdrawal on environmental effectiveness

	Annex B CO2 emissions (compared to business-as-usual in 2010[1])		
	Kyoto Protocol with U.S.	**Kyoto Protocol without U.S.[2]**	**KP plus other provisions**
Hagem and Holtsmark (2001)	- 12.8%	- 3.7%	With ceilings on permit supply: - 7.3%
Den Elzen and de Moor (2001b)[3]	- 5.1%	+ 8%[4]	-
Böhringer (2001)	- 5.8%	- 0.5%	With the Bonn sinks provision: - 0,01%
Böhringer and Löschel (2001)	- 10%	0	If FSU exerts its monopoly power: -3%
Buchner et al. (2001)	- 13.1%	- 6.6%	-
Den Elzen and de Moor (2002)[5]	- 5.2%	- 4.3%[6]	With the Marrakech accords: - 0.6%

All studies apply international emissions trading.

[1] The targets for 2010 imposed by the Kyoto Protocol are related to base year emissions levels, not to the 1990-levels. Therefore, all these studies compare the simulations for emission reductions with respect to the BAU situation in 2010.

[2] Percentage change with respect to the BAU of total Annex B emissions in 2010, including the US emissions.

[3] This analysis compares the CO2 emissions to the 1990-levels.

[4] Excluding the US emissions from the Annex B would imply a reduction in the Annex B emissions of - 4% compared to 1990-levels

[5] This paper uses CO2 equivalent emissions to reflect abatement efforts.

[6] This value does not include the US emissions.

In addition, Table 2 suggests that the remaining Annex B countries would react to the US decision by increasing their own emissions. This prediction seems to be confirmed by the recent outcome of the Marrakech Conference of the Parties, where additional sink provisions have been established which reduce the environmental effectiveness of the Treaty. At the same time, the emissions market loses its largest permit demander, which implies that there is a higher amount of hot air available for the remaining Annex B countries and that the permit price falls. This reduces the cost of energy in the remaining Annex B countries, thus mitigating potential impacts on energy demand (which could possibly rise).

Other studies, in addition to those quoted in Table 2, achieve similar conclusions. Eyckmans et al. (2001) find that in 2010 world carbon emissions would increase by 25.5% with respect to 1990 compared to an increase of 15.5% if the Kyoto Protocol is implemented including the US. Similar conclusions can be found also in Kemfert (2001), Kopp (2001) and Vrolijk (2001).[6]

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 (2001), where a model with endogenous and induced technical change is used. In this paper, the effect of the lower permit price on the incentives to undertake GHG emission reducing R&D are quantified. The results are summarised in Table 3, which confirms the decline of R&D expenditure in all Annex B countries after the US defection from the Kyoto Protocol.

Table 3. Implication of the US withdrawal on the amount of R&D

Changes of R&D expenditure in percentage (Annex B without USA compared to original Annex B)				
	USA	**JPN**	**EU**	**FSU**
2010	- 9.7%	- 0.3%	- 0.6%	- 8.3%
2020	- 12.0%	- 0.3%	- 0.7%	- 7.9%
2030	- 13.7%	- 0.4%	- 0.8%	- 6.7%
2040	- 15.0%	- 0.3%	- 0.7%	- 5.0%
2050	- 15.7%	- 0.2%	- 0.5%	- 3.1%

[6] Including the effects of the Marrakech Agreement reached at the Seventh Conference of the Parties, the decrease in the world abatement is even stronger: Den Elzen and de Moor (2001a, 2002) includes the Marrakech provisions and find that the Annex B CO2 equivalent emissions actually *increase* by almost 2% with respect to the 1990-level.

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. As a consequence, the emission/output ratio deteriorates in all Annex B countries (Buchner, Carraro and Cersosimo, 2001).

Finally, the US decision, by inducing a fall in the permit price, penalises the permit sellers, namely Russia, which loses most of its benefits from participating in the Kyoto agreement (given hot air, a lower permit price strongly reduces Russia's possible windfall profits). However, being the dominant seller, Russia could be tempted to use the banking provision and its monopolistic power to raise the price of permits (Manne and Richels, 2001) [7]. Given the low benefits from emission trading, Russia could even question its participation in the Kyoto Protocol.

This latter threat is reinforced by one of the rules of the Kyoto Protocol, which requires that at least 55 Parties to the Convention, representing at the same time at least 55% of 1990 carbon dioxide emissions of Annex B countries, must ratify the Protocol for it to enter into force. Russia is well aware of its importance as a key player for the agreement implementation. As a consequence, its bargaining power has sharply increased after the US defection from Kyoto. This increased bargaining power has enabled Russia to obtain important concessions in Marrakech, which further reduce the environmental effectiveness of the Protocol.

The above evidence supports our search for negotiation and policy strategies designed to provide new incentives for the US to ratify the Kyoto Protocol. It is indeed crucial to bring the US back into the international climate regime. Without the US contribution no effective emission reductions can be achieved.[8] Can "issue linkage", and in particular the linkage between climate and R&D cooperation, be the right policy tool to induce the US to move back to Kyoto?

3. Can "issue linkage" induce US cooperation? A game-theoretic approach

Let us briefly describe the game-theoretic model upon which our empirical analysis will be based (see Carraro and Siniscalco, 1997, or Carraro and Marchiori, 2001, for a detailed presentation). Assume negotiations take place among n countries, $n \geq 3$, each indexed by i = 1, ..., n. Countries play a two-stage game. In the first stage -- the *coalition game* -- they decide non-cooperatively whether or not to sign the agreement (i.e. to join the coalition). In the second stage, they play a non-cooperative open loop Nash game to set their policy variables (emission abatement rate, investments, R&D expenditure). In the second stage,

[7] Other studies which have addressed the possibility of strategic behaviour on the supply side of the permit market are: Böhringer (2001), Böhringer and Löschel (2001), Buchner, Carraro and Cersosimo (2001), Den Elzen and de Moor (2002, 2001a, 2001b), Egenhofer, Hager and Legge (2001), Eyckmans, van Regemorter and van Steenberghe (2001).

[8] In addition, without the US commitment to reduce their own emissions, developing countries are very unlikely to join the Annex B group.

countries which signed the agreement play as a single player and divide the resulting payoff according to a given burden-sharing rule.[9]

In the empirical model described in the next section, the players are six macro-regions: Europe (EU), Japan (JPN), Former Soviet Union (FSU), United States (US), China (CHN) and Rest of the World (ROW). The starting point of our analysis is the existing climate regime. Therefore, we assume that EU, JPN and FSU are committed to comply with the Kyoto Protocol (even though they have not yet ratified it), namely their abatement rate is such to achieve the Kyoto target. In the second stage, these countries optimally set their investments and R&D expenditure. In contrast, the other countries -- US, CHN and ROW -- maximise their own welfare function with respect to their investments, R&D expenditure and also their abatement rate.

Assume that EU, JPN and FSU identify issue linkage as a strategy to induce the US to accept and ratify the Kyoto Protocol. In particular they want to link climate and R&D cooperation. Is this strategy effective?

The issue linkage proposal that EU, JPN and FSU are assumed to make to the US is as follows. All four countries are offered to cooperate on both climate change control and technological innovation and diffusion. If a country free-rides either on climate cooperation or on R&D cooperation (or on both), it keeps the environmental benefits (because climate control is a public good) but looses the R&D cooperation benefits (at least partly, because of technological spillovers). Is this proposal credible?

Note that the incentives to free-ride on the climate agreement come from the public good nature of climate change control, whereas the incentives to free-ride on the R&D agreement arise from the presence of technological spillovers. Therefore, R&D cooperation is assumed to be an imperfect club good. As suggested by theoretical works (Cf. Carraro and Marchiori, 2001), we will see that the parameter which identifies technological spillovers plays a crucial role in the analysis of the effectiveness and credibility of the issue linkage proposal.

Let us identify the theoretical conditions which are necessary and sufficient for the joint agreement, in which all four countries, including the US, cooperate on both climate and R&D, to be profitable and stable.[10] We will focus on the first stage of the game, in which all countries decide whether or not to cooperate on climate and R&D. It is important to recall that the environmental coalition (EU, JPN, FSU) is assumed to be committed to comply with the Kyoto targets. However, they can set their technological variables in a non cooperative way, if in the first stage they decide not to cooperate on technological innovation and diffusion.

[9] This approach must be contrasted with the traditional cooperative game approach (e.g. Chander and Tulkens, 1995, 1997) and with a repeated game approach (Barrett, 1994, 1997). Moreover, note that the regulatory approach often proposed in public economics is not appropriate given the lack of a supranational authority.

[10] An agreement is profitable if each cooperating player gets a payoff larger than the one he would get when no agreement is signed. An agreement is stable if there is no incentive to free-ride and there is no incentive for other countries to sign the agreement (see Carraro and Marchiori, 2002 for a survey of the theory of coalition stability).

As said, in the business as usual game the following coalition structure forms[11]:

(1) $[(EU, JPN, FSU)_a, EU_{R\&D}, JPN_{R\&D}, FSU_{R\&D}, USA_{a, R\&D}, CHN_{a, R\&D}, ROW_{a, R\&D}]$

namely EU, JPN and FSU cooperate to control GHG emissions, whereas the US free-ride; CHN and ROW also play non-cooperatively. Note that the level of R&D expenditure is set non-cooperatively by all players.

If issue linkage is effective, i.e. the US accept to cooperate on both climate control and technology because they do not want to loose the benefits arising from R&D cooperation, the following coalition structure forms:

(2) $[(EU, JPN, FSU, USA)_{a, R\&D}, CHN_{a, R\&D}, ROW_{a, R\&D}]$

where Annex B countries (EU, JPN, FSU and USA) cooperate on both issues. We will refer to this coalition structure as the "joint coalition structure". CHN and ROW set non cooperatively both their abatement level and their R&D expenditure.

The comparison between (1) and (2) enables us to identify the first necessary condition. Issue linkage is profitable to all Annex B countries if:

(3) $$P_i[(EU, JPN, FSU, USA)_{a, R\&D}, CHN_{a, R\&D}, ROW_{a, R\&D}] >$$
$$P_i[(EU, JPN, FSU)_a, EU_{R\&D}, JPN_{R\&D}, FSU_{R\&D}, USA_{a, R\&D}, CHN_{a, R\&D}, ROW_{a\ R\&D}]$$

where $P_i(.)$ denotes the welfare function of country i and i = EU, JPN, FSU, USA. In words, the situation in which Annex B countries cooperate on both climate and R&D is preferred by all countries to the situation in which EU, JPN, FSU cooperate on climate, USA free-ride and no R&D cooperation takes place.

If the US cooperate on technology but free-ride on climate, the coalition structure is:

(4) $[(EU, JPN, FSU, USA)_{R\&D}, (EU, JPN, FSU)_a, USA_a, CHN_{a, R\&D}, ROW_{a, R\&D}]$

[11] A coalition *C* is any non-empty subset of the player set N. A coalition structure $\pi = \{C_1, C_2, \ldots, C_m\}$ is a partition of the player set N, i.e. $C_i \cap C_j = \emptyset$ for $i \neq j$ and $\cup^m_{i=1} C_i = N$.

This coalition structure leads to a second important group of conditions:

(5a) $P_i[(EU, JPN, FSU, USA)_{a,R\&D}, CHN_{a, R\&D}, ROW_{a, R\&D}] >$

$P_i[(EU, JPN, FSU, USA)_{R\&D}, (EU, JPN, FSU)_a, USA_a, CHN_{a, R\&D}, ROW_{a, R\&D}]$

$i = EU, JPN, FSU$

(5b) $P_{USA}[(EU, JPN, FSU, USA)_{a,R\&D}, CHN_{a, R\&D}, ROW_{a, R\&D}] <$

$P_{USA}[(EU, JPN, FSU, USA)_{R\&D}, (EU, JPN, FSU)_a, USA_a, CHN_{a, R\&D}, ROW_{a, R\&D}]$

Conditions (5a) and (5b) say that (EU, JPN, FSU) should prefer cooperation on both climate and R&D to cooperation on R&D only, otherwise it would not be profitable for these players to propose the US a linked cooperation on both issues. By contrast, the US should prefer to cooperate on R&D only, otherwise there would be no need to introduce issue linkage because the US would find it profitable to cooperate on both issues anyway. Therefore, (3) is the usual profitability or rationality condition, where (5a) and (5b) guarantee that issue linkage is not a trivial situation which profits to all players.

Let us now focus on the stability of the joint agreement. If the US free-ride on either R&D cooperation or climate cooperation (or on both), they loose all benefits because of issue linkage. Therefore, the following coalition structure forms:

(6) $[(EU, JPN, FSU)_{a, R\&D}, USA_{a, R\&D}, CHN_{a, R\&D}, ROW_{a, R\&D}]$

As a consequence, the US have no incentive to free-ride (subject to issue linkage) if:

(7) $P_{USA}[(EU, JPN, FSU, USA)_{a, R\&D}, CHN_{a, R\&D}, ROW_{a, R\&D}] >$

$P_{USA}[(EU, JPN, FSU)_{a, R\&D}, USA_{a, R\&D}, CHN_{a, R\&D}, ROW_{a, R\&D}]$

The other Annex B countries, EU, JPN and FSU, are committed to climate cooperation. Therefore they can only free-ride on R&D cooperation. If the EU free-ride, the coalition structure is

(8) $[(EU, JPN, FSU, USA)_a, (JPN, FSU, USA)_{R\&D}, EU_{R\&D}, CHN_{a, R\&D}, ROW_{a, R\&D}]$

Therefore, the EU has no incentive to free ride on the joint agreement if:

(9) P_{EU} [(EU, JPN, FSU, USA)$_{a, R\&D}$, $CHN_{a, R\&D}$, $ROW_{a, R\&D}$] >

P_{EU} [(EU, JPN, FSU, USA)$_a$, (JPN, FSU, USA)$_{R\&D}$, $EU_{R\&D}$, $CHN_{a, R\&D}$, $ROW_{a, R\&D}$]

Similar conditions must hold for JPN and FSU. As a consequence, the joint agreement is stable if (7), (9) and:

(10) P_{JPN} [(EU, JPN, FSU, USA)$_{a, R\&D}$, $CHN_{a, R\&D}$, $ROW_{a, R\&D}$] >

P_{JPN} [(EU, JPN, FSU, US)$_a$, (EU, FSU, US)$_{R\&D}$, $JPN_{R\&D}$, $CHN_{a, R\&D}$, $ROW_{a, R\&D}$]

(11) P_{FSU} [(EU, JPN, FSU, USA)$_{a, R\&D}$, $CHN_{a, R\&D}$, $ROW_{a, R\&D}$] >

P_{FSU} [(EU, JPN, FSU, USA)$_a$, (EU, JPN, USA)$_{R\&D}$, $FSU_{R\&D}$, $CHN_{a, R\&D}$, $ROW_{a, R\&D}$]

are met. Let us recall that the stability condition (7) is conditional on the adoption of the issue linkage strategy and on its credibility.

There is therefore a final important condition that must be checked for an issue linkage proposal – e.g. the one in which climate and R&D cooperation are linked -- to be an effective tool to induce the US to participate in the Kyoto agreement. This last condition is the credibility of the issue linkage proposal.[12] Is it credible that the environmental coalition (EU, JPN, FSU) actually excludes the US from R&D cooperation if the US do not comply with the Kyoto agreement?

To answer this question, we need to compare the payoffs under the coalition structures (4) and (6). The issue linkage proposal is credible if:

(12) P_i[(EU, JPN, FSU)$_{a, R\&D}$, $USA_{a, R\&D}$, $CHN_{a, R\&D}$, $ROW_{a, R\&D}$] >

P_i[(EU, JPN, FSU, USA)$_{R\&D}$, (EU, JPN, FSU)$_a$, USA_a, $CHN_{a, R\&D}$, $ROW_{a, R\&D}$]

i = EU, JPN, FSU

[12] The issue of the credibility of the threat implicit in the issue linkage proposal has been raised by Tol *et al.* (2000).

i.e. if EU, JPN and FSU prefer the situation in which they implement the threat implicit in the issue linkage proposal to the situation in which they accept the US free-riding on climate but cooperate with the US on R&D. If condition (12) is met, the threat implicit in the issue linkage proposal is credible. Indeed, were (12) not satisfied, EU, JPN and FSU would prefer to maintain at least R&D cooperation with the US.

The above conditions (3) (7) (9) (10) (11) (12) are necessary and sufficient for the profitability and stability of the coalition structure [(EU, JPN, FSU, USA)$_{a,\ R\&D}$, CHN$_{a,\ R\&D}$, ROW$_{a,\ R\&D}$] and for the credibility of the threat upon which it is based. In the next section we will analyse from an empirical viewpoint whether the above conditions are likely to be met.

4. The role of issue linkage: some empirical evidence

In the next subsection, the main assumptions and the modelling framework which will be used to assess the effectiveness of the issue linkage proposal will be described. In particular, the main features of the ETC-RICE model will be highlighted. Then, in the following subsection, the assumptions about scenarios and policy strategies will be implemented into the ETC-RICE model to check the validity of the profitability, stability and credibility conditions presented above.

4.1 Main assumptions and modelling framework

The empirical part of this paper is based on optimisation results obtained using a version of Nordhaus' RICE model in which endogenous and induced technical change are modelled. In our version of Nordhaus' model, called ETC-RICE, 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.[13] The ETC-RICE model has already been used in Buonanno, Carraro, Castelnuovo and Galeotti (2000), Buonanno, Carraro and Galeotti (2001) and in Buchner, Carraro and Cersosimo (2001). A brief description is contained in the Appendix.

In the model, six countries/regions (US, EU, JPN, FSU, China and ROW) optimally set the intertemporal values of three strategic variables: investments, R&D expenditure and abatement rate. Given the interdependency of countries' decisions, the equilibrium value of these variables is the solution of a dynamic open-loop Nash game between the six countries/regions.

As said, when a country commits to reduce its own GHG emissions, its abatement rate is such to achieve the Kyoto target. By contrast, countries that do not comply with the Kyoto Protocol implement the welfare

[13] This idea is supported by the existing empirical research on the environmental Kuznets curves, which seems to support the conclusion that economic growth is associated with a decreasing emission-output ratio (see Galeotti and Lanza, 2001 for some recent results).

maximising abatement rate (conditionally on the cooperative strategy of countries in the Kyoto/Bonn/Marrakech coalition). Note that countries/regions which adhere to the Kyoto/Bonn/Marrakech agreement are assumed to meet the Kyoto constraints from 2010 onward.[14] We thus adopt the so-called "Kyoto forever" hypothesis (Manne and Richels, 2001). Therefore, our reference to the Kyoto/Bonn agreement is partly imprecise since, for the sake of brevity, we will call "Kyoto Protocol" or "Kyoto/Bonn/Marrakech agreement" a "Kyoto forever" scenario. This is already a standard practice adopted in most economic analyses of climate policy.

As for the other strategic variables, they are optimally set by all countries. Those which belong to a coalition maximise the coalition joint welfare. Those outside the coalition maximise their own individual welfare. This is also true with respect to R&D expenditure, whose optimal value depends, among other things, upon the international technological spillovers and the coalition (internal) technological spillovers.

It is important to clarify the role of spillovers in the model. In order to capture the idea that countries which do not belong to the R&D coalition are excluded from the benefits produced by R&D cooperation, we add a new parameter to the standard ETC-RICE model, denoted by β. This parameter quantifies the increased share of world knowledge which is appropriated by countries belonging to the R&D coalition. This parameter is equivalent to the "differential technological spillover" or "coalition information exchange coefficient" in the theoretical model by Carraro and Siniscalco (1995, 1997).

Therefore, in the model there are 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. As shown in the Appendix, 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. Given the crucial role of β in the analysis of the effectiveness of issue linkage, we will explore how the empirical assessment of the theoretical conditions described in the previous section depends on the value of β.

A final important assumption concerns the policy scenario. We will analyse the effectiveness of issue linkage in inducing the US to comply with the Kyoto Protocol under the assumption that all GHG abatement is carried out through domestic emission reduction policies. In other words, we analyse only the case in which international emission trading is not allowed. The reason is the following one. Our goal is to check the effectiveness of R&D issue linkage. To do this, we adopt the most favourable situation for issue linkage to be effective. This situation is the one in which there is no international trading.

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[14] The use of the "Kyoto forever" hypothesis is a strong assumption. However, the CO2 concentration levels implicit in this assumption (if RICE is a good description of the world) coincide with those in the A1B scenario (IPCC, 2001) which can be considered the "median" scenario among those currently proposed.

It is well known that an international trading scheme is a cost-effective way to reduce GHG emissions, i.e. the cost of reducing emissions is lowest, if an international and competitive trading market is at work. At the same time, recent studies have highlighted the strong impact of an international emission trading market on R&D and technological innovation. In particular, Buonanno, Carraro and Galeotti (2001) 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. Hence, R&D and emission trading are strategic substitutes. As a consequence, countries have the largest incentive to attain the benefits yielded by R&D cooperation when international emission trading is not allowed. The issue linkage proposal, which prevents the US in attaining the R&D cooperation benefits if they do not comply with the Kyoto targets, is thus most effective when the US need R&D and technological innovation to achieve the Kyoto targets. In other words, we evaluate the impact of issue linkage in a situation in which environmentally committed countries (EU, JPN and FSU) have the maximum possible amount of R&D to offer to convince the US to move back to the Kyoto agreement.

4.2 Empirical analysis

Let us start by evaluating the non triviality of the issue linkage proposal. As formalised in eqs. (5a) and (5b), this is the case when the environmental coalition (EU, JPN, FSU) prefers to cooperate on both climate and R&D than to cooperate on R&D only. By contrast the US prefer cooperation only on R&D.

Table 4 provides an empirical assessment of (5a) and (5b) both in the short run (the first commitment period) and in the medium run (up to 2050). Table 4 shows that the issue linkage proposal is not trivial. In the short run for $\beta \geq 0.66$. In the medium run, for all values of β.[15] In particular, for these values of β, the US prefer to cooperate only on R&D rather than on both climate and R&D.

The next question concerns the profitability of the issue linkage proposal. Is it convenient for all Annex B countries to cooperate on both climate and R&D (with respect to the present situation)? The answer is provided by Table 5, where the profitability condition (3) is assessed both in the short and in the medium run.

Table 5 shows that, if $\beta \geq 0.66$, all Annex B countries find it profitable to move from the current situation to an international regime in which all Annex B countries cooperate on both GHG emission control and on technological innovation and diffusion. Note that the country for which the profitability condition is most

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[15] For simplicity, in all tables we do not write the entire coalition structure but we omit developing countries (CHN and ROW). The reason is that, as explained in section 3, these countries are assumed not to cooperate in all coalition structures.

difficult to be met is the US. In all other Annex B countries, the profitability of issue linkage is achieved for all values of β. There are two reasons which explain this result.

Table 4. Non triviality of the issue linkage proposal.

First commitment period (1990-2010)

	P[(USA, JPN, EU, SU)$_{A,R\&D}$]						P[(USA, JPN, EU, FSU)$_{R\&D}$; (JPN, EU, FSU)$_A$ USA$_A$]					
b	**0.10**	**0.20**	**0.33**	**0.66**	**1.00**	**1.50**	**0.10**	**0.20**	**0.33**	**0.66**	**1.00**	**1.50**
USA	12.0621	12.0745	12.0897	12.1231	12.1524	12.1881	12.0808	12.0944	12.1096	12.1435	12.1730	12.2090
JPN	6.4105	6.4107	6.4111	6.4121	6.4133	6.4149	6.4084	6.4087	6.4090	6.4098	6.4107	6.4124
EU	14.9212	14.9281	14.9364	14.9549	14.9712	14.9908	14.9200	14.9264	14.9349	14.9533	14.9692	14.9891
FSU	1.8844	1.8845	1.8845	1.8847	1.8848	1.8850	1.8843	1.8844	1.8845	1.8846	1.8847	1.8849

P[(USA, JPN, EU, SU)$_{A,R\&D}$] ^{3} P[(USA, JPN, EU, FSU)$_{R\&D}$; (JPN, EU, FSU)$_A$ USA$_A$]						
b	**0.10**	**0.20**	**0.33**	**0.66**	**1.00**	**1.50**
USA	no	No	no	no	no	no
JPN	yes	Yes	yes	yes	yes	yes
EU	yes	Yes	yes	yes	yes	yes
FSU	yes	Yes	no	yes	yes	yes

Medium term (1990-2050)

	P[(USA, JPN, EU, SU)$_{A,R\&D}$]						P[(USA, JPN, EU, FSU)$_{R\&D}$; (JPN, EU, FSU)$_A$ USA$_A$]					
b	**0.10**	**0.20**	**0.33**	**0.66**	**1.00**	**1.50**	**0.10**	**0.20**	**0.33**	**0.66**	**1.00**	**1.50**
USA	22.4161	22.4425	22.4741	22.5429	22.6031	22.6777	22.5083	22.5339	22.5665	22.6366	22.6952	22.7742
JPN	12.1728	12.1736	12.1757	12.1797	12.1843	12.1875	12.1704	12.1711	12.1725	12.1761	12.1788	12.1840
EU	27.9150	27.9287	27.9468	27.9862	28.0161	28.0618	27.9043	27.9185	27.9367	27.9758	28.0095	28.0506
FSU	3.8871	3.8872	3.8875	3.8879	3.8883	3.8887	3.8868	3.8870	3.8872	3.8876	3.8880	3.8884

P[(USA, JPN, EU, SU)$_{A,R\&D}$] ^{3} P[(USA, JPN, EU, FSU)$_{R\&D}$; (JPN, EU, FSU)$_A$ USA$_A$]						
b	**0.10**	**0.20**	**0.33**	**0.66**	**1.00**	**1.50**
USA	no	No	no	no	no	no
JPN	yes	Yes	yes	yes	yes	yes
EU	yes	Yes	yes	yes	yes	yes
FSU	yes	Yes	yes	yes	yes	yes

P(.): payoffs (cumulated discounted consumption)
β: differential technological spillover or coalition information exchange coefficient

Firstly, the US move from a situation of no cooperation on both climate and R&D to a situation of cooperation on both issues. The other countries already cooperate on GHG emission control. In particular, the US, by leaving the situation in which they free-ride on climate control, start paying for abatement costs.

Secondly, the US are characterised by high R&D expenditure levels. Therefore, when cooperating on R&D, the US provide, via spillovers, important technological benefits to the other partners. As a consequence, these partners, EU, JPN and FSU, achieve profitability even for low values of β.

Table 5. Profitability of the issue linkage proposal

First commitment period (1990-2010)

	P[(JPN, EU, FSU)$_{A}$ USA$_{A}$]	P[(USA, JPN, EU, FSU)$_{A,R\&D}$]					
b		0.10	0.20	0.33	0.66	1.00	1.50
USA	12.1126	12.0621	12.0745	12.0897	12.1231	12.1524	12.1881
JPN	6.3642	6.4105	6.4107	6.4111	6.4121	6.4133	6.4149
EU	14.8579	14.9212	14.9281	14.9364	14.9549	14.9712	14.9908
FSU	1.8838	1.8844	1.8845	1.8845	1.8847	1.8848	1.8850

	P[(USA, JPN, EU, FSU)$_{A,R\&D}$] 3 P[(JPN, EU, FSU)$_{A}$ USA$_{A}$]					
b	0.10	0.20	0.33	0.66	1.00	1.50
USA	no	No	no	yes	yes	yes
JPN	yes	Yes	yes	yes	yes	yes
EU	yes	Yes	yes	yes	yes	yes
FSU	yes	Yes	yes	yes	yes	yes
All	no	No	no	yes	yes	yes

Medium term (1990-2050)

	P[(JPN, EU, FSU)$_{A}$ USA$_{A}$]	P[(USA, JPN, EU, FSU)$_{A,R\&D}$]					
b		0.10	0.20	0.33	0.66	1.00	1.50
USA	22.5259	22.4161	22.4425	22.4741	22.5429	22.6031	22.6777
JPN	12.1190	12.1728	12.1736	12.1757	12.1797	12.1843	12.1875
EU	27.8559	27.9150	27.9287	27.9468	27.9862	28.0161	28.0618
FSU	3.8860	3.8871	3.8872	3.8875	3.8879	3.8883	3.8887

	P[(USA, JPN, EU, FSU)$_{A,R\&D}$] 3 P[(JPN, EU, FSU)$_{A}$ USA$_{A}$]					
b	0.10	0.20	0.33	0.66	1.00	1.50
USA	no	No	no	yes	yes	yes
JPN	yes	Yes	yes	yes	yes	yes
EU	yes	Yes	yes	yes	yes	yes
FSU	yes	Yes	yes	yes	yes	yes
All	no	No	no	yes	yes	yes

P(.): payoffs (cumulated discounted consumption)
β: differential technological spillover or coalition information exchange coefficient

Now, let us analyse the free-riding incentives which could de-stabilise the joint agreement in which all Annex B countries cooperate on both climate control and R&D. The US have no free-riding incentives if condition (7) is met. The empirical assessment of condition (7) is shown in Table 6.

Table 6. U.S. incentives to free ride on the issue linkage proposal

First commitment period (1990-2010)

	P[(USA, JPN, EU, FSU)$_{A,R\&D}$]						P[(JPN, EU, FSU)$_{A,R\&D}$ USA$_{A,R\&D}$]					
b	**0.10**	**0.20**	**0.33**	**0.66**	**1.00**	**1.50**	**0.10**	**0.20**	**0.33**	**0.66**	**1.00**	**1.50**
USA	12.0621	12.0745	12.0897	12.1231	12.1524	12.1881	12.0678	11.9631	12.0078	11.9719	12.0332	12.0229

	P[(USA, JPN, EU, FSU)$_{A,R\&D}$] 3 P[(JPN, EU, FSU)$_{A,R\&D}$ USA$_{A,R\&D}$]					
b	**0.10**	**0.20**	**0.33**	**0.66**	**1.00**	**1.50**
USA	no	yes	yes	yes	yes	yes

Medium term (1990-2050)

	P[(USA, JPN, EU, FSU)$_{A,R\&D}$]						P[(JPN, EU, FSU)$_{A,R\&D}$ USA$_{A,R\&D}$]					
b	**0.10**	**0.20**	**0.33**	**0.66**	**1.00**	**1.50**	**0.10**	**0.20**	**0.33**	**0.66**	**1.00**	**1.50**
USA	22.4161	22.4425	22.4741	22.5429	22.6031	22.6777	22.5172	22.3200	22.4452	22.3643	22.4379	22.5235

	P[(USA, JPN, EU, FSU)$_{A,R\&D}$] 3 P[(JPN, EU, FSU)$_{A,R\&D}$ USA$_{A,R\&D}$]					
b	**0.10**	**0.20**	**0.33**	**0.66**	**1.00**	**1.50**
USA	no	yes	yes	yes	yes	yes

P(.): payoffs (cumulated discounted consumption)
β: differential technological spillover or coalition information exchange coefficient

Given that the profitability condition is met for β ≥ 0.66, it is important to explore the stability of the linked agreement only for values of β ≥ 0.66. Table 6 actually shows that the US has no incentive to free-ride on the coalition which cooperates on both climate and R&D when free-riding on either climate or R&D (or both) implies the loss of the benefits arising from technological cooperation.

A similar conclusion holds for the other Annex B countries. By evaluating conditions (9), (10) and (11), we conclude that no Annex B country has an incentive to free-ride on the linked agreement for values of β ≥ 0.66 (both in the short and in the medium run).

Our empirical analysis is summarised by Table 7, which shows for which values of β the profitability and stability conditions are met.

Table 7. Values of b for which the profitability and stability conditions are met.

	1990-2010	1990-2050
P[(USA, JPN, EU, FSU)$_{A,R\&D}$] ³ P[(JPN, EU, FSU)$_{A}$ USA$_{A}$]	β ³ 0.66	β ³ 0.66
P[(USA, JPN, EU, FSU)$_{A,R\&D}$] ³ P[(JPN, EU, FSU)$_{A,R\&D}$ USA $_{A,R\&D}$]	β ³ 0.20	β ³ 0.20
P[(USA, JPN, EU, FSU)$_{A,R\&D}$] ³ P[(USA, JPN, EU, FSU)$_{A}$ (USA, JPN, FSU)$_{R\&D}$ EU$_{R\&D}$]	β ³ 0.10	β ³ 0.10
P[(USA, JPN, EU, FSU)$_{A,R\&D}$] ³ P[(USA, JPN, EU, FSU)$_{A}$ (USA, EU, FSU)$_{R\&D}$ JPN$_{R\&D}$]	β ³ 0.10	β ³ 0.10
P[(USA, JPN, EU, FSU)$_{A,R\&D}$] ³ P[(USA, JPN, EU, FSU)$_{A}$ (USA, EU, JPN)$_{R\&D}$ FSU$_{R\&D}$]	β ³ 0.10	β ³ 0.10

P(.): payoffs (cumulated discounted consumption)
β: differential technological spillover or coalition information exchange coefficient

Therefore, the proposal of linking R&D cooperation with cooperation on climate change control is not trivial, it is profitable, and above all it guarantees the stability of the linked agreement (no incentive to free-ride once the linked agreement is signed).

However, is the issue linkage proposal credible? The answer depends on condition (12), which says that EU, JPN and FSU should prefer to implement the threat implicit in the issue linkage proposal rather than accepting the US free-riding on climate control and the US cooperation on technological innovation and diffusion.

Unfortunately, our empirical results suggest that this last condition is unlikely to be met, i.e. the threat implicit in the issue linkage proposal is unlikely to be credible. Table 8 demonstrates that, at least in the medium run, the credibility condition is not met for all values of β, and in particular for all $\beta \geq 0.66$. The situation is slightly more positive in the short run, where the credibility condition is met for $\beta = 0.66$. Therefore, only in the short run and in a neighbourhood of the values of β for which the issue linkage proposal is both profitable and stable, the credibility condition could be met.

The intuition for this result is as follows. The benefits from technological cooperation are much higher for the EU, JPN, and above all the FSU, than for the US. Therefore, the EU, JPN and FSU suffer a bigger loss when the issue linkage threat is implemented. In addition, the environmental benefits arising from cooperation on climate change control are smaller, at least in the ETC-RICE model, than the technological benefits from R&D cooperation. Therefore, EU, JPN and FSU prefer to loose the environmental benefits than the technological benefits, and thus accept the US free-riding on climate cooperation if the US cooperate on R&D.

Table 8. Credibility of the issue linkage proposal

First commitment period (1990-2010)

	P[(JPN, EU, SU)$_{A,R\&D}$ USA$_{A,R\&D}$]						P[(USA, JPN, EU, FSU)$_{R\&D}$; (JPN, EU, FSU)$_{A}$ USA$_{A}$]					
b	**0.10**	**0.20**	**0.33**	**0.66**	**1.00**	**1.50**	**0.10**	**0.20**	**0.33**	**0.66**	**1.00**	**1.50**
JPN	6.3711	6.4380	6.1892	6.4358	6.3480	6.1751	6.4084	6.4087	6.4090	6.4098	6.4107	6.4124
EU	14.5540	14.9548	14.8310	14.9629	14.9175	14.8674	14.9200	14.9264	14.9349	14.9533	14.9692	14.9891
FSU	1.8626	1.8849	1.8838	1.8850	1.8573	1.8840	1.8843	1.8844	1.8845	1.8846	1.8847	1.8849

P[(JPN, EU, FSU)$_{A,R\&D}$ USA$_{A,R\&D}$] 3 P[(USA, JPN, EU, FSU)$_{R\&D}$; (JPN, EU, FSU)$_{A}$ USA$_{A}$]						
b	**0.10**	**0.20**	**0.33**	**0.66**	**1.00**	**1.50**
JPN	no	yes	no	yes	no	no
EU	no	yes	no	yes	no	no
FSU	no	yes	no	yes	no	no

Medium term (1990-2050)

	P[(JPN, EU, SU)$_{A,R\&D}$ USA$_{A,R\&D}$]						P[(USA, JPN, EU, FSU)$_{R\&D}$; (JPN, EU, FSU)$_{A}$ USA$_{A}$]					
b	**0.10**	**0.20**	**0.33**	**0.66**	**1.00**	**1.50**	**0.10**	**0.20**	**0.33**	**0.66**	**1.00**	**1.50**
JPN	12.0942	12.1824	11.9787	12.1862	12.1073	12.0746	12.1704	12.1711	12.1725	12.1891	12.1788	12.1840
EU	27.6532	27.9117	27.8183	27.9313	27.9804	27.9072	27.9043	27.9185	27.9367	27.9758	28.0095	28.0506
FSU	3.8766	3.8866	3.8879	3.8869	3.8808	3.8890	3.8868	3.8870	3.8872	3.8876	3.8880	3.8894

P[(JPN, EU, FSU)$_{A,R\&D}$ USA$_{A,R\&D}$] 3 P[(USA, JPN, EU, FSU)$_{R\&D}$; (JPN, EU, FSU)$_{A}$ USA$_{A}$]						
b	**0.10**	**0.20**	**0.33**	**0.66**	**1.00**	**1.50**
JPN	no	yes	no	no	no	no
EU	no	no	no	no	no	no
FSU	no	no	yes	no	no	no

P(.): payoffs (cumulated discounted consumption)
β: differential technological spillover or coalition information exchange coefficient

The above results therefore make the issue linkage proposal unlikely to be effective in inducing the US to reconsider their decision to withdraw from the Kyoto Protocol. However, they open the way to another policy strategy and to a different international regime on climate change control, which will be analysed in the next section.

5. The environmental effectiveness of a climate regime based on technological cooperation

The results proposed in the previous section provide little support to a policy strategy structured around the linkage between climate and R&D negotiations. Even if "issue linkage" proves to be effective in inducing a profitable and stable coalition structure, in which all Annex B countries cooperate on both climate and R&D, the conclusion is not in favour of "issue linkage". The reason, as explained above, is that the R&D issue linkage proposal is based on an implicit non credible threat (Tol *et al*. 2000). Countries like the EU, JPN and FSU prefer to cooperate with the US on technological innovation and diffusion, even when the US free-ride on climate cooperation.

This latter result shows a strong incentive to technological cooperation among Annex B countries. Therefore, it may be linked to recent proposals highlighting the idea that technological cooperation can be the appropriate tool to deal with the global warming problem[16].

In particular, Barrett (2001) argues that the Kyoto Protocol provides poor incentives for participation and compliance. He also argues that an alternative climate regime could be structured as follows. A cooperative funding of basic Research and Development with respect to energy-saving, environment-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.

Barrett emphasises that this approach -- based on a R&D Protocol with complementary standards protocols -- derives its attractiveness from the inclusion of both "push" incentives affecting the supply of R&D and "pull" incentives aimed at the demand for the fruits of R&D. In contrast, the Kyoto Protocol does not consider the necessity to push R&D, but only the pull incentives. By also focussing on incentives related to the funding of R&D, preconditions for long-term technical innovation and diffusion are created. Moreover, this approach does not require the enforcement of compliance, while providing incentives for participation.

Note that, the more countries to adopt a standard, the more attractive it becomes for other countries to adopt the same standard. This highlights the strategic advantage of Barrett's idea. A further advantage consists in the avoidance of leakage and free-riding: non-participants cannot use the products of collective R&D in order to reduce their emissions more cheaply.[17]

In this section, we do not want to discuss the many pros and cons of Barrett's (2001) proposal. We would rather explore whether:

(a) there are actually the incentives for R&D cooperation to be implemented by Annex B countries, namely the coalition in which Annex B countries cooperate only on technological innovation and diffusion is profitable and stable;

[16] See for example Barrett (2001), Edmonds, Roop and Scott (2000), Edmonds (2001), Flannery (2001), Jacoby (1998).

[17] The focus on R&D and on long-term incentives does not undermine the Kyoto process but could even be incorporated under the UNFCCC. In particular, the Kyoto agreement could be imbedded in Barrett's approach.

(b) cooperation on technological innovation and diffusion, without cooperation on GHG emission abatement, is also environmental effective, i.e. reducing global emissions.

(c) this latter conclusion holds, if not when Annex B countries cooperate on R&D, at least when all world countries cooperate on technological innovation and diffusion, i.e. when a global coalition forms.

These three issues can be explored by using the ETC-RICE model, because in this model R&D expenditure is one of countries’ strategic variables and because accumulated knowledge (the sum of past R&D expenditures) affects both economic growth and the emission/output ratio. In addition, the presence of internal spillovers makes R&D cooperation increasingly profitable (profitability increases with the parameter β, as seen in the previous section, and with the number of signatories).

In this section, we present an empirical assessment of two possible scenarios: the first one is characterised by technological cooperation among the four “traditional” Kyoto countries/regions (USA, EU, JPN, FSU), while the second one features the grand coalition where all world countries cooperate on technological innovation and diffusion. For each scenario, we assess the profitability, stability and environmental effectiveness of technological cooperation.

Our results can be summarised as follows. As expected, and as suggested by economic theory (Yi, 1997), *the coalition in which either Annex B countries or all countries cooperate only on R&D is profitable and stable for values of b ³ 0.2.* Therefore, as soon as the excludable benefits arising from technological cooperation become relevant ($\beta \geq 0.2$), all countries find it profitable to cooperate. In addition, there is no incentive to free-ride on technological cooperation. Again, the reason lies in the presence of economic benefits (parameterised by β) that can be appropriated only by coalition members (this also captures Barrett’ s argument about technological standards).

The crucial issue is therefore the environmental effectiveness of a coalition in which member countries cooperate on R&D only. Our results are summarised in Tables 9 and 10. The first column shows different values of the parameter β, which parameterises technological spillovers internal to the coalition. The second column contains the change of global emissions when R&D cooperation is implemented with respect to global emissions in the current situation in which EU, JPN and FSU fulfil the Kyoto target, the other countries free-ride on climate cooperation 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 current situation). While the second and the third columns show the results in the first commitment period (1990-2010), the fourth and the fifth columns show what could happen in the medium term (1990-2050).

Table 9 illustrates that both global emissions and the emission/output ratio increase when Annex B countries cooperate only on R&D. Note that there are no cases in which technological cooperation can induce a reduction of global emissions and/or of the emission/output ratio (at least as far as the ETC-RICE model can adequately capture the dynamics of induced technical change) .

Table 9. Environmental effectiveness of technological cooperation between Annex B countries

Technological cooperation between Annex B countries vs. environmental cooperation between EU, JPN, FSU				
	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%

β: differential technological spillover or coalition information exchange coefficient

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).

These negative conclusions on the environmental effectiveness of an international regime 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 post Bonn situation in which only EU, JPN and FSU are committed to comply with the Kyoto target[18].

The reason 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 CHN and ROW (which do not participate in the technological agreement and therefore get part of the benefits at no cost).

[18] 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) with a situation which is characterised by no mandatory emission reduction targets.

Can more satisfactory conclusions be achieved if a global technological cooperation, which involves all world countries, be established? Again, even though global cooperation increases the economic benefits and the environmental effectiveness of the agreement, total emissions in the new regime – in which countries cooperate only on technological innovation and diffusion -- increase with respect to total emissions in the current regime (see Table 10). The increase of emissions is smaller when all world regions cooperate to develop and diffuse climate-friendly technologies with respect to 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.

Table 10. Environmental effectiveness of global technological cooperation

Global technological cooperation vs. environmental cooperation among EU, JPN, FSU				
	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%

β: differential technological spillover or coalition information exchange coefficient

Also note that, at least in the short run (Table 9), 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, where the emission-output ratio improves, thus lowering the global increase of emissions (Table 10).

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 induces a relative environmental improvement of production technologies -- our analysis does not seem to support the idea that a coalition devoted only to technological cooperation can also have a positive impact on climate change control.

Therefore, the tentative conclusion is that technological cooperation cannot replace environmental cooperation. Within the limits of the ETC-RICE, our optimisation experiments suggest 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, may be necessary. These measures could also provide additional incentives to invest in climate friendly technological change.

Some results, already discussed in Section 4, provide support to this last statement. Indeed, 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.

Therefore, a mix of climate and technological cooperation seems to provide the best equilibrium outcome. However, this policy mix can hardly be achieved on a voluntary basis, unless the US climate policy strategy recognises the benefits arising from combining technological and climate cooperation.

6. Conclusions

A large cooperation on global environmental issues is difficult to achieve because of the public nature of the global environment that creates strong incentives to free-ride. This problem, often highlighted in the game-theoretic and economic literature, is also confirmed by recent events in climate policy. The most obvious example is the US decision not to ratify the Kyoto Protocol.

The US defection induces serious environmental and economic problems, ranging from a deterioration of the environmental effectiveness of the Kyoto Protocol to the increase in Russia’s bargaining power. Therefore, it is crucial to investigate whether an incentive strategy indeed exists that can induce the US to revise their decision and to comply with the Kyoto commitments.

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. In this paper, we have considered the linkage of climate cooperation with technological cooperation. The idea is that the incentives to appropriate R&D cooperation benefits, which can be obtained only by cooperating also on climate change control, could offset the incentives to free-ride on the environmental dimension.

Our analysis does not seem to provide empirical support to the issue linkage proposal. Linkage between climate and R&D cooperation does not seem to be an effective strategy to induce the US to move back to Kyoto. Even though the coalition structure in which all Annex B cooperate on both dimensions (climate and R&D) is profitable, the issue linkage proposal is based on an implicit non-credible threat. Countries like the

European Union, Japan and Russia prefer to cooperate with the US on technological innovation and diffusion even when the US free-ride on climate cooperation.

The strong preference for technological cooperation among Annex B countries that emerges from our analysis indicates that another climate regime, recently proposed in literature, should be explored. This climate regime is based on the idea that a cooperation focussed only on R&D innovation and diffusion, without any binding abatement commitment, could be the appropriate tool to deal with the global warming problem. However, our results suggest that technological cooperation without environmental cooperation cannot yield lower global GHG emissions, even though it increases growth and welfare.

As in previous papers (e.g. Buchner, Carraro and Cersosimo, 2001), our results must be taken cautiously. This paper aims at identifying economic mechanisms and feedbacks, rather than providing precise quantitative assessments of the implications of different climate regimes. The structure of the ETC-RICE model, albeit simple, clearly identifies the numerous effects that must be taken into account when comparing alternative climate policies and international regimes. The role of endogenous and induced technical change is shown to be very important. The use of strategic R&D investments and R&D cooperation open new possibilities to climate policy. This paper has explored these possibilities by taking into account the economic mechanisms behind endogenous growth, climate-friendly innovation, international R&D spillovers and the possibility to exclude (at least partially) some countries from fully enjoying the benefits of these spillovers (RJVs and patents are obvious tools).

The above set of economic mechanisms has been parameterised. As a consequence, the results are sensitive to this parameterisation, even though a sensitivity analysis with respect to the most important parameter -- the coalition information exchange coefficient -- has been carried out. The conclusions of our study are not in favour of R&D issue linkage, or of R&D cooperation alone, as ways to replace the Kyoto Protocol to curb GHG emissions. However, these conclusions should be tested using other models and other specifications of technical change.

Nonetheless, our results suggest that the technological dimension remains a very important feature of any climate policy, and that R&D cooperation can be an important complement to the Kyoto Protocol.

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Appendix. The ETC-RICE model with international technology diffusion and differential technological spillovers.

The ETC-RICE model with differential technological spillovers (or coalition information exchange benefits) 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 interactions 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 a 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 output gross 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 (1997) 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 (BAU) 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 also the emission-output ratio. Finally, international technological spillovers are also modelled.

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 ETC case) of all other players.

The Standard Model without Induced Technical Change

As said above, 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). Thus, 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:

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

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 $(n=1,\dots6)$. 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 maintain 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:

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

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:

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

where Y is output net of climate change effects (specified just as 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:

$$E(n,t) = \sigma(n,t)[1-\mu(n,t)]Q(n,t) \qquad (4)$$

where σ can be loosely defined as the emissions-output ratio, E stands for emissions and μ 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 σ. 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.[19] More precisely, the RICE emission-output relationship is modified as follows:

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

In (4'), knowledge reduces the emissions-output ratio with an elasticity of α_n, which is also region-specific; the parameter χ_n is a scaling coefficient, whereas ς_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 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 one.

Knowledge Spillovers

Previous formulations do not include potential spillovers effects produced by knowledge, and therefore ignore the fact that both technologies and organisational structures diffuse 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.

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[19] 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 of specifying variables and calibrating parameters for which there is no immediately available and sound information in the literature.

Following Weyant and Olavson (1999), who suggest that the definition of spillovers in the induced technical change context be kept plain and simple - in 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 knowledge spillovers, the stock of world knowledge is introduced in the third version of the ETC-RICE model, both in the production function and in the emission-output ratio equation.

This formulation enables us to introduce differential technological spillovers, i.e. the coalition information exchange coefficient β, in a simple manner. This parameter determines the level of additional world knowledge from which the regions in the same R&D coalition can benefit. Equations (1) and (4') are then revised as follows:

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

and:

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

where the stock of world knowledge:

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

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