119

■

Dynamic core-theoretic cooperation in a two-dimensional international environmental model

Marc Germain, Alphonse Magnus, Henry Tulkens

March 2010

ENVIRONMENTAL
ECONOMICS & MANAGEMENT
MEMORANDUM

UCL
Université
catholique
de Louvain

Chair Lhoist Berghmans
in Environmental Economics
and Management

Center for Operations Research
and Econometrics (CORE)

Mathematical Social Sciences 59 (2010) 208–226

Contents lists available at ScienceDirect

Mathematical Social Sciences

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

Dynamic core-theoretic cooperation in a two-dimensional international environmental model☆

Marc Germain [a,b,*], Henry Tulkens [c], Alphonse Magnus [d]

[a] *Laboratoire EQUIPPE, Université de Lille-3, France*
[b] *Department of Economics, Université catholique de Louvain, Belgium*
[c] *CORE, Université catholique de Louvain, Belgium*
[d] *Institut de mathématique, Université catholique de Louvain, Belgium*

ARTICLE INFO

Article history:
Received 16 February 2009
Received in revised form
8 September 2009
Accepted 6 October 2009
Available online 20 October 2009

JEL classification:
Q54
Q58
F42
F53
O21

Keywords:
Stock pollutant
Capital accumulation
International environmental agreements
Dynamic core solution

ABSTRACT

This article deals with cooperation issues in international pollution problems in a two-dimensional dynamic framework implied by the accumulation of the pollutant and of the capital goods. Assuming that countries do reevaluate at each period the advantages to cooperate or not given the current stocks of pollutant and capital, and under the assumption that damage cost functions are linear, we define at each period of time a transfer scheme between countries, which makes cooperation better for each of them than non-cooperation. This transfer scheme is also strategically stable in the sense that it discourages partial coalitions.

☆ The authors wish to thank their colleagues Guillaume Rocheteau, Gérard Hamiache, Aart the Zeeuw, Russell Cooper and Parkash Chander for their valuable discussions and, for their hospitality and support, the Chair Lhoist Berghmans at CORE as well as the Department of Economics at the National University of Singapore.
* Corresponding author at: Department of Economics, Université catholique de Louvain, Belgium.
E-mail addresses: marc.germain@univ-lille3.fr (M. Germain), henry.tulkens@uclouvain.be (H. Tulkens), alphonse.magnus@uclouvain.be (A. Magnus).

0165-4896/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.mathsocsci.2009.10.003

0. Introduction

This paper extends to a two-dimensional setting – pollutant emissions and investment in capital goods – the dynamic game-theoretic results established for the one-dimensional model of international environmental agreements by Germain et al. (1998b) (closed loop, linear case) and by Germain et al. (2003) (closed loop, nonlinear case).

Economically, a serious limitation of these contributions is that in the model they use, pollution abatement is independent of investment and of capital accumulation, so that growth of the economies is either absent or exogenous. There is indeed only one control variable for each country, namely the level of its emissions and, for the economy taken as a whole, only one state variable. The economic model is one of partial equilibrium cost minimization. The aim of this paper is to broaden the perspective by considering investment in each country as a second control variable as well as the country's accumulated capital as a second state variable. The economic model thus moves towards one of general equilibrium utility maximization.

In this context, the central issue of these two papers is taken up again here, namely whether stable and efficient cooperation among countries in the core-theoretic sense of a cooperative game at each period can be established, possibly using appropriately designed transfers. As in the two previous papers, a positive answer is obtained in terms of a sequence of self-enforcing cooperative international agreements, that we call a coalitionally (or strategically) stable path of the economic-ecological system. [1] Here as in Germain et al. (1998a,b), damage cost functions are assumed linear. Thus far, the nonlinear case of Germain et al. (2003) remains open for a similar extension.[2]

The issues raised by the necessity of cooperation amongst the countries involved in an transfrontier pollution problem if a social optimum is to be achieved, have been addressed in the literature in terms of game theory concepts starting with static (one shot) games (see Mäler (1989), followed by Chander and Tulkens (1992), Kaitala et al. (1995)). These are only suitable for flow pollution models. Stock pollutant problems introduce an intertemporal dimension, for which dynamic game theory is a more appropriate tool of analysis, as is done in e.g. van der Ploeg and de Zeeuw (1992), Kaitala et al. (1992), Hoel (1992), Tahvonen (1994), Petrosjan and Zaccour (1995).

Except for the last one, the other four contributions leave aside the issue of the *voluntary* implementation of the international optimum. This is an important drawback since no supranational authority can be called upon to impose the optimum in a context where the countries' interest in cooperation diverges strongly between one another, and especially if some countries loose when the social optimum is implemented. In view of ensuring such implementation, it was already shown in the static case by Tulkens (1979) that there exists feasible transfers between the countries involved that would provide incentives towards cooperation. This property, understood later as inducing strategies belonging to the core of a cooperative game, has in effect been demonstrated for a static game by Chander and Tulkens (1995, 1997), who propose a specific transfer scheme achieving the stated purpose. This result has been extended by Germain et al. (1998a) to the larger context of open loop dynamic games, and thereafter to closed loop (or feedback) dynamic games in the two papers mentioned at the outset. For a similar approach where transfers guarantee dynamic individual rationality understood as time-consistency and agreeability (with an application to a international pollution problem), see Jorgensen et al. (2003).

The structure of the present paper is as follows. Section 1 presents the international stock pollutant model with capital accumulation in each country. In Section 2, transfers are formulated so as to ensure that each country is not worse off when it participates in an international agreement, compared to a no agreement situation described as a Nash equilibrium. Section 3 computes the main variables of the

[1] Another concept of coalitional stability, called "internal and external stability" and due to d'Aspremont and Jaskold Gabszewicz (1986), was introduced in an international environmental dynamic game by Rubio and Ulph (2007), leading to quite different results than those obtained here as to the formation of the grand coalition.

[2] The nonlinear case was treated in an open loop setting by Eyckmans and Tulkens (2003). Coalitional stability was also established there, albeit of a substantially different kind due to the open loop assumption.

model, including the transfers, at each period. Section 4 presents a theorem establishing that a specific form of the transfers achieves coalitional stability in the sense of the core of a cooperative game.

1. Preliminaries

1.1. Components of the model

Our economic model is written in discrete time. Consider n countries indexed by $i \in \mathcal{N} = \{1, 2, \ldots, n\}$ and some planning period $\mathcal{T} = \{1, 2, \ldots, T\}$ (T, the planning horizon, is a positive integer, possibly infinite). In the following, all variables (production, investment, capital stock, pollutant emissions, pollution stock) are positive, the first three of which are economic while the last two are ecological. We therefore deal with an economic-ecological model.

Each country i is characterized by an aggregate production function:

$$y_{it} = F_i(k_{it}, e_{it}) \tag{1}$$

where y_{it}, k_{it}, e_{it} are respectively the production, the stock of capital and the consumption of energy of country i at time t. We assume throughout that F_i satisfies the standard properties of a neo-classical production function, as reported in the following assumption:

Assumption 1. The function $F_i : R_+^2 \longrightarrow R_+$ *satisfies the following conditions:*

(i) $f(0, 0) = 0$.
(ii) f *is twice continuously differentiable.*
(iii) $f_k(k, e) > 0$ *and* $f_e(k, e) > 0$, *for all* k, e.
(iv) $f_e(k, 0) = +\infty$, *for all* $k > 0$.
(v) f *is differentiably strictly concave jointly in* (k, e), *i.e.*

$$f_{kk} < 0, \qquad f_{ee} < 0, \quad \text{and} \quad f_{kk}f_{ee} - f_{ke}^2 > 0.$$

All components of this assumption are standard in production theory and have well known economic interpretations.

The capital stock is assumed to accumulate following:

$$k_{it} = [1 - \delta_i]k_{i,t-1} + h_{it}, \quad i \in \mathcal{N} \tag{2}$$

where h_{it} is investment of country i at date t, δ_i is the rate of depreciation of capital in country i ($0 < \delta_i < 1$), and $k_{i0} > 0$ is the given initial stock of capital.

Pollution emitted by a country is assumed to be proportional to its energy consumption. For the sake of simplicity and without loss of generality, we denote the two quantities by the same symbol.Thus $\mathbf{e_t} = (e_{1t}, \ldots, e_{nt})'$ is the vector of the different countries' emissions of a certain pollutant at time t. These emissions spread uniformly in the atmosphere and contribute to a stock of pollutant z according to the equation

$$z_t = [1 - \gamma]z_{t-1} + \sum_{i=1}^{n} e_{it} \tag{3}$$

where the initial stock of pollutant z_0 is given and where γ is the pollutant's natural rate of degradation ($0 < \gamma < 1$). As described in (3), the current stock is a linear function of the inherited stock z_{t-1} and of the current emissions $\mathbf{e}_t$.This model describes, for example, the basics of the climate change problem where the flows of emissions of greenhouse gases accumulate into a stock, which only gradually assimilates and which is the cause of the climate change.

The stock of pollutant causes damages to each country's environment. For country i ($i \in \mathcal{N}$), these damages during period t are measured in monetary terms by the function $D_i(z_t)$, where D_i is supposed to be a linear function of the current stock z_t:

Assumption 2. The function $D_i : R_+ \to R_+$ is of the form:

$$D_i(z_t) = \pi_i z_t \tag{4}$$

where π_i is positive number.

Finally, let for each $i \in \mathcal{N}$

$$W_i = \sum_{t=1}^{T} \rho^{t-1} \left[F_i(k_{i,t}, e_{i,t}) - h_{i,t} - \pi_i z_t \right] \tag{5}$$

denote the discounted sum of the stream of collective consumption enjoyed by the population of country i over the planning period $\mathcal{T}$, where $0 < \rho < 1$ is a discount factor.

Bringing together all the above, we call the resulting model an "economic-ecological system". For such a system, any $(3n + 1)T$-dimensional vector $\{(e_{i,t}, h_{i,t}, k_{i,t}, z_t), i \in \mathcal{N}, t \in \mathcal{T}\}$ satisfying (2) and (3) constitutes a feasible path for the planning period $\mathcal{T}$, yielding each country i a collective consumption (5).

1.2. Non-cooperative vs cooperative behaviors and the issue of coalitional stability

For the so described international economy with environmental interactions, we deal in this paper with two planning issues, each of which corresponds to an alternative behavioral assumption on the countries' policies regarding pollutant emissions. In the first case we assume that each country i simply pursues its own interest in its choice of both emission and investment policies, $(e_{i,t}, t \in \mathcal{T})$ and $(h_{i,t}, t \in \mathcal{T})$ respectively, ignoring the external effects induced by the former on the other countries through the stock accumulation process described by Eq. (3). Such behavior is formally expressed, for each country, by the solution of the dynamic optimization problem consisting in maximizing the value of (5) with respect to the control variables e_{it} and h_{it}, subject to the constraints (2) and (3) whereby the state variables $(k_{i,t}, t \in \mathcal{T}, i \in \mathcal{N})$ and $(z_t, t \in \mathcal{T})$, respectively, are defined. Internationally, the outcome of such parallel behaviors is in the nature of a Nash equilibrium of a non-cooperative game in which the players are the countries and their strategies are the policies just mentioned. We call this outcome the Non-cooperative Nash Equilibrium (NCNE) and denote it $(\bar{e}_{i,t}, i \in \mathcal{N}, t \in \mathcal{T})$, $(\bar{h}_{i,t}, i \in \mathcal{N}, t \in \mathcal{T})$ and $(\bar{z}_t, t \in \mathcal{T})$.

In the second case, the assumption is made that while still seeking their interest as expressed by (5), all countries also do take into account the external effects induced on the other countries by their emission decisions. This is formalized by the solution of the alternative, and single, dynamic optimization problem consisting in maximizing the sum over all i's of (5) with respect to all control variables e_{it} and h_{it}, $i = 1, 2, \ldots, n$, subject as before to (2) and (3) whereby the state variables are defined. Internationally, the outcome of such coordinated behaviors is in the nature of Pareto efficient strategies of the cooperative version of the game defined above. We call this outcome the International Optimum (IO) and denote it $(e^{\mathcal{N}}_{i,t}, i \in \mathcal{N}, t \in \mathcal{T})$, $(h^{\mathcal{N}}_{i,t}, i \in \mathcal{N}, t \in \mathcal{T})$ and $(z^{\mathcal{N}}_t, t \in \mathcal{T})$.

The well known difference between the Nash equilibrium and Pareto efficient solutions just stated prompts the following normative question: can a policy instrument be devised whereby the countries would be induced to move away from the Nash equilibrium trajectory, which is inefficient, and adopt instead the Pareto efficient one, while being assured that they would not loose from this move, neither individually nor by forming coalitions? This is exactly what is achieved by the Chander–Tulkens transfer scheme mentioned above whose dynamic extension by Germain et al. (1998a,b) was formulated for the one-dimensional case only. We now turn to the two-dimensional economic setting introduced in the previous subsection.

2. Transfers to stabilize the international optimum

The matter is handled by backward induction.

2.1. The transfers at the final time T

2.1.1. The partial Nash equilibrium w.r.t. a coalition U at time T

If a coalition forms, there first should be specified which state of the system is going to prevail, that is, which paths are going to be followed by the countries. For that purpose, we transpose to the present dynamic context a concept introduced by Chander and Tulkens (1997) and define the partial Nash equilibrium w.r.t. a coalition U at time T (PANE_U$_T$) as follows. Let U be a subset of $\mathcal{N}$ formed by countries that behave cooperatively *between themselves*.The other countries are assumed to behave individually. Formally, for given $\mathbf{k}_{\mathcal{N},T-1} =_{def} \left\{k_{i,T-1}, i \in \mathcal{N}\right\}$ and z_{T-1}:
(i) the members of coalition U maximize jointly the sum of their utilities:

$$\max_{\mathbf{h}_{UT},\mathbf{e}_{UT}} \sum_{i\in U} [F_i(k_{iT}, e_{iT}) - h_{iT} - \pi_i z_T] \tag{6}$$

where $\mathbf{h}_{U,T} =_{def} \{h_{iT}, i \in U\}$, $\mathbf{e}_{U,T} =_{def} \{e_{iT}, i \in U\}$, under constraints (2) and (3) and taking $e_{j,T}, h_{j,T}$ $(\forall j \notin U)$ as given.
(ii) each country outside the coalition solves:

$$\max_{h_{iT},e_{iT}} F_i(k_{iT}, e_{iT}) - h_{iT} - \pi_i z_T, \quad i \notin U \tag{7}$$

under constraints (2) and (3), and taking $e_{j,T}, h_{j,T}$ $(\forall j \neq i)$ as given.

Given (2), the previous objectives can be equivalently maximized w.r.t. $\mathbf{k}_T$ and $\mathbf{e}_T$. The simultaneous solution of these problems leads to a set of FOC that fully characterize the PANE_U$_T$:
(i) for the members of coalition U:

$$\frac{\partial F_i}{\partial k_{iT}} = 1 \tag{8}$$

$$\frac{\partial F_i}{\partial e_{iT}} = \pi_U =_{def} \sum_{j\in U} \pi_j \tag{9}$$

(ii) for a country outside the coalition:

$$\frac{\partial F_i}{\partial k_{iT}} = 1 \tag{10}$$

$$\frac{\partial F_i}{\partial e_{iT}} = \pi_i. \tag{11}$$

Let $k_{iT}^U, e_{iT}^U (i \in \mathcal{N})$ be the solution of the FOC (8)–(11) and

$$z_T^U = [1-\gamma]z_{T-1} + \sum_{i=1}^{n} e_{iT}^U. \tag{12}$$

The payoffs of the countries are given by the following value functions:

$$w_{iT}^U(k_{i,T-1}, z_{T-1}) = F_i(k_{iT}^U, e_{iT}^U) - k_{iT}^U + [1-\delta_i]k_{i,T-1} - \pi_i z_T^U, \quad i \in \mathcal{N} \tag{13}$$

so that the payoff of coalition U is given by the value function:

$$\begin{aligned} W_T^U(\mathbf{k}_{U,T-1}, z_{T-1}) &= \sum_{i\in U} w_{iT}^U(k_{i,T-1}, z_{T-1}) \\ &= \sum_{i\in U} \left[F_i(k_{iT}^U, e_{iT}^U) - k_{iT}^U + [1-\delta_i]k_{i,T-1} - \pi_i z_T^U\right] \end{aligned} \tag{14}$$

where $\mathbf{k}_{U,T-1} =_{def} \left\{k_{i,T-1}, i \in U\right\}$.

2.1.2. Two particular cases

The PANE_U$_T$ generalizes the two important particular outcomes mentioned earlier, namely the NCNE and the IO. Indeed on the one hand, the non-cooperative Nash equilibrium at time T (NCNE$_T$) is obtained when the coalition is a singleton ($U = v =_{def} \{i\}$ for any i), i.e. all countries are assumed to behave individually. Then the payoffs of the countries are given by the following value functions:

$$w_{iT}^{v}(k_{i,T-1}, z_{T-1}) = F_i(k_{iT}^{v}, e_{iT}^{v}) - k_{iT}^{v} + [1-\delta_i]k_{i,T-1} - \pi_i z_T^{v}, \quad i \in \mathcal{N} \tag{15}$$

where k_{iT}^{v}, e_{iT}^{v} are the solution of the FOC (8)–(11) when $U = v$, and

$$z_T^{v} = [1-\gamma]z_{T-1} + \sum_{i=1}^{n} e_{iT}^{v}. \tag{16}$$

On the other hand, the international optimum at date T (IO$_T$) obtains when the coalition contains all countries ($U = \mathcal{N}$) and all members are supposed to maximize jointly the sum of their utilities. The payoff of country i at the optimum is given by the following value function:

$$w_{iT}^{\mathcal{N}}(k_{i,T-1}, z_{T-1}) = F_i(k_{iT}^{\mathcal{N}}, e_{iT}^{\mathcal{N}}) - k_{iT}^{\mathcal{N}} + [1-\delta_i]k_{i,T-1} - \pi_i z_T^{\mathcal{N}} \tag{17}$$

so that the global payoff of all countries is given by the value function:

$$\begin{aligned} W_T^{\mathcal{N}}(\mathbf{k}_{\mathcal{N},T-1}, z_{T-1}) &= \sum_{i=1}^{n} w_{iT}^{\mathcal{N}}(k_{i,T-1}, z_{T-1}) \\ &= \sum_{i\in\mathcal{N}} \left[F_i(k_{iT}^{\mathcal{N}}, e_{iT}^{\mathcal{N}}) - k_{iT}^{\mathcal{N}} + [1-\delta_i]k_{i,T-1} - \pi_i z_T^{\mathcal{N}}\right] \end{aligned} \tag{18}$$

where $\mathbf{k}_{\mathcal{N},T-1} =_{def} \left\{k_{i,T-1}, i \in \mathcal{N}\right\}$, $k_{iT}^{\mathcal{N}}, e_{iT}^{\mathcal{N}} (i \in \mathcal{N})$ are the solution of the FOC (8)–(11) when $U = \mathcal{N}$, and

$$z_T^{\mathcal{N}} = [1-\gamma]z_{T-1} + \sum_{i=1}^{n} e_{iT}^{\mathcal{N}}. \tag{19}$$

By definition of the optimum, one verifies that

$$W_T^{\mathcal{N}}(\mathbf{k}_{\mathcal{N},T-1}, z_{T-1}) \geq \sum_{i=1}^{n} w_{iT}^{U}(k_{i,T-1}, z_{T-1}), \quad \forall U \subset \mathcal{N}. \tag{20}$$

Thus, from a collective point of view, the IO$_T$ is preferable to any solution of the partial agreement type, the least preferred being the NCNE$_T$. The difference $W_T^{\mathcal{N}}(\mathbf{k}_{\mathcal{N},T-1}, z_{T-1}) - \sum_{i=1}^{n} w_{iT}^{v}(k_{i,T-1}, z_{T-1})$ is called by Chander and Tulkens (1997) the *ecological surplus* resulting from international cooperation.

However (20) may not be sufficient to ensure cooperation.[3] Indeed if $\exists U \subset \mathcal{N}$ for which $\sum_{i\in U} w_{iT}^{\mathcal{N}}(k_{i,T-1}, z_{T-1}) < W_T^{U}(\mathbf{k}_{U,T-1}, z_{T-1})$, then coalition U will not cooperate without compensation for the lower payoff it obtains.

2.1.3. Transfers

Since the horizon of time is limited to the single period $t = T$, one can use the transfers formula proposed by Chander and Tulkens (1997) in a static framework. The idea is that the required compensation can be achieved by an appropriate sharing of the ecological surplus. Let

$$\begin{aligned} \theta_{iT}(\mathbf{k}_{\mathcal{N},T-1}, z_{T-1}) &= -[w_{iT}^{\mathcal{N}}(k_{i,T-1}, z_{T-1}) - w_{iT}^{v}(k_{i,T-1}, z_{T-1})] \\ &\quad + \frac{\pi_i}{\pi_{\mathcal{N}}}\left[W_T^{\mathcal{N}}(\mathbf{k}_{\mathcal{N},T-1}, z_{T-1}) - \sum_{i=1}^{n} w_{iT}^{v}(k_{i,T-1}, z_{T-1})\right] \end{aligned} \tag{21}$$

[3] This is why we refrain from calling the IO an international *cooperative* optimum, as is often, and mistakenly, asserted in the literature. Cooperation results from individual and coalitional rationality; efficiency, i.e. the fulfilment of (18), is not a sufficient condition for cooperation.

be the transfer (>0 if received, <0 if paid) to country i at time T, where $\pi_{\mathcal{N}} =_{def} \sum_{i\in\mathcal{N}} \pi_i$. By construction, the budget of the transfers defined by (21) is balanced, i.e.

$$\sum_{i=1}^{n} \theta_{iT}(\mathbf{k}_{T-1}, z_{T-1}) = 0. \tag{22}$$

Then at the international optimum country i's payoff *including* transfers becomes:

$$\begin{aligned}\widetilde{w}_{iT}^{\mathcal{N}}(\mathbf{k}_{\mathcal{N},T-1}, z_{T-1}) &= w_{iT}^{\mathcal{N}}(k_{i,T-1}, z_{T-1}) + \theta_{iT}(\mathbf{k}_{\mathcal{N},T-1}, z_{T-1}) \\ &= w_{iT}^{v}(k_{i,T-1}, z_{T-1}) + \frac{\pi_i}{\pi_{\mathcal{N}}}\left[W_T^{\mathcal{N}}(\mathbf{k}_{\mathcal{N},T-1}, z_{T-1}) - \sum_{i=1}^{n} w_{iT}^{v}(k_{i,T-1}, z_{T-1})\right].\end{aligned} \tag{23}$$

Since the ecological surplus is positive, one has:

$$\begin{aligned}&\widetilde{w}_{iT}^{\mathcal{N}}(\mathbf{k}_{\mathcal{N},T-1}, z_{T-1}) - w_{iT}^{v}(k_{i,T-1}, z_{T-1}) \\ &= \frac{\pi_i}{\pi_{\mathcal{N}}}[W_T^{\mathcal{N}}(\mathbf{k}_{\mathcal{N},T-1}, z_{T-1}) - \sum_{i=1}^{n} w_{iT}^{v}(k_{i,T-1}, z_{T-1})] \geq 0, \quad \forall i \in \mathcal{N}.\end{aligned} \tag{24}$$

Thus cooperation with the transfers (21) is *individually rational* at time T, in the sense that each country is better off at the IO *with these transfers* than at the non-cooperative Nash equilibrium,

Following Chander and Tulkens (1997), one also has the following stronger result[4]:

$$\sum_{i\in U} \widetilde{w}_{iT}^{\mathcal{N}}(k_{i,T-1}, z_{T-1}) \geq W_T^{U}(\mathbf{k}_{U,T-1}, z_{T-1}), \quad \forall U \subset \mathcal{N} \tag{25}$$

i.e. cooperation with transfers is *coalitionally rational, or self-enforcing* at time T, in the sense that any coalition would enjoy only a lower payoff than the one it would obtain at the IO_T *with transfers,* if it were to defect from this IO_T and revert to the PANE_T w.r.t. itself. In terms of game theory, such a property is summarized by saying that the vector $(\widetilde{w}_{iT}^{\mathcal{N}}, i \in N)$ is an imputation that belongs to the core of a cooperative game associated with the economic model. Full details are given in the paper just quoted.

2.2. The transfers at earlier periods

Countries know that, whatever they do previously to T, transfers exist (defined by (21) that make the IO_T preferable for each of them with respect to all other solutions. The problem we wish to consider now is whether transfers can be designed that make all countries interested in cooperating for periods previous to T as well.

Let us suppose that there exists a sequence of transfers that makes the IO_τ's preferable for all countries at times $\{\tau = t + 1, \dots, T\}$. We make two important behavioral assumptions:
(i) these transfers induce effectively cooperation from $t + 1$ onwards,[5] and
(ii) *all* countries therefore (rationally) expect at t that they will cooperate in all subsequent periods $\{t + 1, \dots, T\}$.

Given these assumptions, we show in the following that it is indeed possible to define transfers that make the IO_t preferable for all countries at time t.

[4] The proof of their Theorem 1 carries over directly to the present case because the variables $k_{i,T-1}$ and z_{T-1} only play a parametrical role here. The expression (25) holds whatever the inherited stock of pollutant z_{T-1} and the vector of capital stocks $\mathbf{k}_{\mathcal{N},T-1}$.

[5] Note that, following Chander and Tulkens (1997), section 5), one could indeed obtain the cooperative optimum with transfers as an equilibrium, called *ratio equilibrium*.

2.2.1. The partial fallback equilibrium w.r.t. a coalition U at time t

Let U be a subset of $\mathcal{N}$ formed by countries that behave cooperatively *between themselves at t* (while expecting international cooperation sustained by transfers from $t+1$ onwards) and take the other countries' investment and energy consumption as given. This coalition will thus hold only for period t. The other countries are assumed to behave individually. Formally, for given $\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}$:
(i) the members of coalition U maximize jointly the sum of their utilities:

$$\max_{\mathbf{h}_{U,t},\mathbf{e}_{U,t}} \sum_{i\in U} \left[F_i(k_{i,t}, e_{i,t}) - h_{i,t} - \pi_i z_t + \rho \widetilde{w}^{\mathcal{N}}_{it+1}(\mathbf{k}_{\mathcal{N},t}, z_t)\right] \tag{26}$$

where $\mathbf{h}_{U,t} =_{def} \left\{h_{i,t}, i \in U\right\}$, $\mathbf{e}_{U,t} =_{def} \left\{e_{i,t}, i \in U\right\}$, under constraints (2) and (3), taking $e_{j,t}, h_{j,t}$ $(\forall j \notin U)$ as given and $\widetilde{w}^{\mathcal{N}}_{it+1}(\mathbf{k}_{\mathcal{N},t}, z_t)$ is defined as in (23) where t is substituted for T. $\widetilde{w}^{\mathcal{N}}_{it+1}(\mathbf{k}_{\mathcal{N},t}, z_t)$ is the future payoff obtained by country i at the IO's during $\{t+1, \ldots, T\}$.
(ii) each country outside the coalition solves:

$$\max_{h_{i,t},e_{i,t}} F_i(k_{i,t}, e_{i,t}) - h_{i,t} - \pi_i z_t + \rho \widetilde{w}^{\mathcal{N}}_{it+1}(\mathbf{k}_{\mathcal{N},t}, z_t), \quad i \notin U \tag{27}$$

under constraints (2) and (3), taking $e_{j,t}, h_{j,t}$ $(\forall j \neq i)$ as given.

As before, given (2), the previous objectives can be equivalently maximized w.r.t. $\mathbf{k}_t$ and $\mathbf{e}_t$. Solving simultaneously these problems leads to a set of FOC that fully characterize the partial fallback equilibrium w.r.t. coalition U at time t (PAFE_U$_t$):
(i) for the members of coalition U:

$$\frac{\partial F_i}{\partial k_{i,t}} = 1 - \rho \sum_{i\in U} \frac{\partial \widetilde{w}^{\mathcal{N}}_{it+1}}{\partial k_{i,t}} \tag{28}$$

$$\frac{\partial F_i}{\partial e_{i,t}} = \pi_U - \rho \sum_{i\in U} \frac{\partial \widetilde{w}^{\mathcal{N}}_{it+1}}{\partial z_t} \tag{29}$$

(ii) for a country outside the coalition:

$$\frac{\partial F_i}{\partial k_{i,t}} = 1 - \rho \frac{\partial \widetilde{w}^{\mathcal{N}}_{it+1}}{\partial k_{i,t}}, \tag{30}$$

$$\frac{\partial F_i}{\partial e_{i,t}} = \pi_i - \rho \frac{\partial \widetilde{w}^{\mathcal{N}}_{it+1}}{\partial z_t}. \tag{31}$$

Let $k^U_{i,t}, e^U_{i,t} (i \in \mathcal{N})$ be the solutions of the FOC (28)–(31), and $z^U_t = [1-\gamma]z_{t-1} + \sum_{i=1}^n e^U_{i,t}$. Then the payoffs of the countries are given by the following value functions:

$$w^U_{i,t}(k_{i,t-1}, z_{t-1}) = F_i(k^U_{i,t}, e^U_{i,t}) - k^U_{i,t} + [1-\delta_i]k_{i,t-1} - \pi_i z^U_t + \rho \widetilde{w}^{\mathcal{N}}_{it+1}(\mathbf{k}^U_{\mathcal{N},t}, z^U_t), \quad i \in \mathcal{N} \tag{32}$$

so that the payoff of coalition U is given by the value function:

$$\begin{aligned} W^U_t(\mathbf{k}_{U,t-1}, z_{t-1}) &= \sum_{i\in U} w^U_{i,t}(k_{i,t-1}, z_{t-1}) \\ &= \sum_{i\in U} \left[F_i(k^U_{i,t}, e^U_{i,t}) - k^U_{i,t} + [1-\delta_i]k_{i,t-1} - \pi_i z^U_t + \rho \widetilde{w}^{\mathcal{N}}_{it+1}(\mathbf{k}^U_{\mathcal{N},t}, z^U_t)\right] \end{aligned}$$

where $\mathbf{k}_{U,t-1} =_{def} \left\{k_{i,t-1}, i \in U\right\}$. Notice that all the above is defined for $t < T$.

The value function W^U_t so derived from the behaviors (26) and (27) of every coalition and its complement, constitutes together with (18) for $U = \mathcal{N}$, what has been called in Germain et al. (2003, sections 4.1 and 4.2) the γ-characteristic function, defined at time t, of a dynamic cooperative game. The "γ" qualification refers to the specification (27) of the behavior of the non-members of U, introduced and discussed in detail in Chander and Tulkens (1995, 1997).

2.2.2. Two particular cases

As before, the PAFE_U$_t$, $t < T$ generalizes two important particular cases: the fallback non-cooperative equilibrium and the international optimum. These are similar but not identical to the parallel cases defined above for $t = T$.

2.2.2.1. The fallback non-cooperative equilibrium at time t(FNCE$_t$). The fallback non-cooperative equilibrium is obtained when the coalition is a singleton ($U = v = \{i\}$ for any $i \in \mathcal{N}$), i.e. all countries are assumed to behave in an individualistic manner at time t (and cooperatively afterwards). Then the payoffs of the countries are given by the following value functions:

$$w_{i,t}^{v}(k_{i,t-1}, z_{t-1}) = F_i(k_{i,t}^{v}, e_{i,t}^{v}) - k_{i,t}^{v} + [1-\delta_i]k_{i,t-1} - \pi_i z_t^{v} + \rho \widetilde{w}_{it+1}^{\mathcal{N}}(\mathbf{k}_{\mathcal{N},t}^{v}, z_t^{v}), \quad i \in \mathcal{N} \quad (33)$$

where $k_{i,t}^{v}, e_{i,t}^{v}$ are solution of the FOC (28)–(31) when $U = v$, and

$$z_t^{v} = [1-\gamma]z_{t-1} + \sum_{i=1}^{n} e_{i,t}^{v}. \quad (34)$$

For every $t < T$, the key difference between the FNCE$_t$ and the NCNE$_T$ lies in the presence of the terms $\rho \widetilde{w}_{it+1}^{\mathcal{N}}$ in (33) compared to (15): this is where our behavioral assumption on expectations comes into play.

2.2.2.2. The international optimum at time t(IO$_t$). The international optimum is obtained when the coalition contains all countries ($U = \mathcal{N}$). Thus all countries are supposed to behave cooperatively (i.e. they maximize jointly the sum of their utilities) at time t as well as in the whole future. The payoff of country i at the IO is given by the following value function:

$$w_{i,t}^{\mathcal{N}}(k_{i,t-1}, z_{t-1}) = F_i(k_{i,t}^{\mathcal{N}}, e_{i,t}^{\mathcal{N}}) - k_{i,t}^{\mathcal{N}} + [1-\delta_i]k_{i,t-1} - \pi_i z_t^{\mathcal{N}} + \rho \widetilde{w}_{it+1}^{\mathcal{N}}(\mathbf{k}_{\mathcal{N},t}^{\mathcal{N}}, z_t^{\mathcal{N}}), \quad i \in \mathcal{N} \quad (35)$$

where $\mathbf{k}_{\mathcal{N},t} =_{def} \left\{k_{i,t}, i \in \mathcal{N}\right\}$, $k_{it}^{\mathcal{N}}, e_{it}^{\mathcal{N}} (i \in \mathcal{N})$ are solution of the FOC (28)–(31) when $U = \mathcal{N}$, and

$$z_t^{\mathcal{N}} = [1-\gamma]z_{t-1} + \sum_{i=1}^{n} e_{it}^{\mathcal{N}} \quad (36)$$

Thus the global payoff of all countries is given by the value function:

$$\begin{aligned} W_t^{\mathcal{N}}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}) &= \sum_{i=1}^{n} w_{i,t}^{\mathcal{N}}(k_{i,t-1}, z_{t-1}) \\ &= \sum_{i \in \mathcal{N}} \left[F_i(k_{i,t}^{\mathcal{N}}, e_{i,t}^{\mathcal{N}}) - k_{i,t}^{\mathcal{N}} + [1-\delta_i]k_{i,t-1} - \pi_i z_t^{\mathcal{N}} + \rho \widetilde{w}_{it+1}^{\mathcal{N}}(\mathbf{k}_{\mathcal{N},t}^{\mathcal{N}}, z_t^{\mathcal{N}})\right]. \quad (37) \end{aligned}$$

By definition of the IO, one verifies that

$$W_t^{\mathcal{N}}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}) \geq \sum_{i=1}^{n} w_{i,t}^{U}(k_{i,t-1}, z_{t-1}), \quad \forall U \subset \mathcal{N}. \quad (38)$$

From a collective point of view, the IO$_t$ is preferable to any solution of the partial agreement type.

However (38) may not be sufficient to ensure cooperation. Indeed if $\exists U \subset \mathcal{N}$ such that $\sum_{i \in U} w_{it}^{\mathcal{N}}(k_{i,t-1}, z_{t-1}) < W_t^{U}(\mathbf{k}_{U,t-1}, z_{t-1})$, then coalition U will not cooperate without compensation for the lower payoff it obtains.

2.2.3. Transfers at time t

To induce all countries to cooperate to the achievement of the international optimum at time t, we proceed as in period T (see Section 2.1.3). Let

$$\begin{aligned} \theta_{i,t}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}) &= -[w_{i,t}^{\mathcal{N}}(k_{i,t-1}, z_{t-1}) - w_{i,t}^{v}(k_{i,t-1}, z_{t-1})] \\ &\quad + \frac{\pi_i}{\pi_{\mathcal{N}}}\left[W_t^{\mathcal{N}}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}) - \sum_{i=1}^{n} w_{i,t}^{v}(k_{i,t-1}, z_{t-1})\right] \quad (39) \end{aligned}$$

be the transfer (>0 if received, <0 if paid) to country i at time t, where as before $\pi_{\mathcal{N}} = \sum_{i\in\mathcal{N}} \pi_i$. By construction, the budget of the transfers defined by (39) is balanced, i.e.

$$\sum_{i=1}^{n} \theta_{i,t}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}) = 0. \tag{40}$$

The difference $W_t^{\mathcal{N}}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}) - \sum_{i=1}^{n} w_{i,t}^{v}(k_{i,t-1}, z_{t-1})$ is the ecological surplus resulting from the *extension* of international cooperation to period t. Then at the international optimum country i's payoff *including* transfers becomes

$$\begin{aligned}\widetilde{w}_{i,t}^{\mathcal{N}}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}) &= w_{i,t}^{\mathcal{N}}(k_{i,t-1}, z_{t-1}) + \theta_{i,t}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}) \\ &= w_{i,t}^{v}(k_{i,t-1}, z_{t-1}) + \frac{\pi_i}{\pi_{\mathcal{N}}}\left[W_t^{\mathcal{N}}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}) - \sum_{i=1}^{n} w_{i,t}^{v}(k_{i,t-1}, z_{t-1})\right]. \end{aligned}\tag{41}$$

Since the ecological surplus is positive, one has:

$$\begin{aligned}\widetilde{w}_{i,t}^{\mathcal{N}}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}) - w_{i,t}^{v}(k_{i,t-1}, z_{t-1}) &= \frac{\pi_i}{\pi_{\mathcal{N}}}\left[W_t^{\mathcal{N}}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}) - \sum_{i=1}^{n} w_{i,t}^{v}(k_{i,t-1}, z_{t-1})\right] \\ &\geq 0, \quad \forall i \in \mathcal{N}.\end{aligned}$$

Thus cooperation with transfers is *individually rational* at time t, in the sense that each country is better off at the IO_t *with transfers* than at the $FNCE_t$, whatever the inherited stock of pollutant z_{t-1} and the vector of capital stocks $\mathbf{k}_{\mathcal{N},t-1}$.

In Section 4 below, we generalize Chander and Tulkens (1997) result to our dynamic setting and show that:

$$\sum_{i\in U} \widetilde{w}_{i,t}^{\mathcal{N}}(k_{i,t-1}, z_{t-1}) \geq W_t^{U}(\mathbf{k}_{U,t-1}, z_{t-1}), \quad \forall U \subset \mathcal{N},\ \forall t \in \mathcal{T} \tag{42}$$

i.e. cooperation with transfers is *rational in the sense of coalitions* at time t, in the sense that a coalition would enjoy a lower payoff than the one it would obtain at the IO_t *with transfers,* whatever the inherited stock of pollutant z_{t-1} and the vector of capital stocks $\mathbf{k}_{\mathcal{N},t-1}$. This is similar to the core property mentioned above with (25) for $t = T$. It is here extended to all $t < T$.

We have thus shown that:

- at time T, the IO_T with transfers is preferable for all countries to what they would obtain either as a member of a coalition or individually (in the sense of the $PANE\_U_T$ defined above);

- if $\forall \tau = t+1, \ldots, T$, the IO_τ with transfers is preferable for all countries to what they would obtain either as a member of a coalition or individually (in the sense of the $PAFE\_U_t$ defined above), then the IO_t with transfers is also preferable at time t.

Proceeding backwards from $t = T$ to $t = 1$, the final result is that all countries cooperate in each period (no coalition will ever form). This determines the emission and the capital stock levels in each period and also the trajectory of the stock of pollutant, given its initial value z_0. In turn this trajectory determines the values of the functions w_i^{v}, $w_i^{\mathcal{N}}$ and $\widetilde{w}_i^{\mathcal{N}}$, and therefore also the values of the transfers θ_i.

In the infinite horizon case, the backward reasoning considered above applies no more. However, we can consider the stationary solution by taking advantage of the fact that (i) the production functions F_i and damage functions D_i do not depend directly on time as well as (ii) the sharing parameters $\pi_i/\pi_{\mathcal{N}}$ not to depend directly on time either. The functional forms of the solutions thus only vary in time through the varying stocks $\mathbf{k}$ and z. The structure of the problem is then the same as in the finite horizon case.

3. Solution

We now compute the trajectories of the emissions, the capital stocks, the pollutant stock, as well as the values of the payoffs and of the transfers.

3.1. The system of equations

For each[6] $U \subseteq \mathcal{N}$ and each $t \in \mathcal{T}$, the PAFE_U$_t$ is characterized by the following payoffs:

$$W_t^U(\mathbf{k}_{U,t-1}, z_{t-1}) = \max_{\mathbf{k}_{U,t},\mathbf{e}_{U,t}} \left\{ \sum_{i\in U} \left[F_i(k_{i,t}, e_{i,t}) - k_{i,t} + [1-\delta_i]k_{i,t-1} - \pi_i z_t \right.\right.$$
$$\left.\left. + \rho w_{i,t+1}^v \left(k_{i,t}, z_t\right) + \rho \frac{\pi_i}{\pi_{\mathcal{N}}} \left[W_{t+1}^{\mathcal{N}}(\mathbf{k}_{\mathcal{N},t}, z_t) - \sum_{j\in\mathcal{N}} w_{j,t+1}^v(k_{j,t}, z_t) \right]\right]\right\} \quad (43)$$

$$w_{i,t}^U(k_{i,t-1}, z_{t-1}) = \max_{k_{i,t},e_{i,t}} \left\{ F_i(k_{i,t}, e_{i,t}) - k_{i,t} + [1-\delta_i]k_{i,t-1} - \pi_i z_t + \rho w_{i,t+1}^v \left(k_{i,t}, z_t\right) \right.$$
$$\left. + \rho \frac{\pi_i}{\pi_{\mathcal{N}}} \left[W_{t+1}^{\mathcal{N}}(\mathbf{k}_{\mathcal{N},t}, z_t) - \sum_{j\in\mathcal{N}} w_{j,t+1}^v(k_{j,t}, z_t) \right] \right\}, \quad i \notin U \quad (44)$$

under constraint (3), with terminal values $W_{T+1}^U(\mathbf{k}_{U,T}, z_T) = w_{i,T+1}^U(k_{i,T}, z_T) = 0$. We observe that $W_t^U(\mathbf{k}_{U,t-1}, z_{t-1})$ and $w_{i,t}^U(k_{i,t-1}, z_{t-1})$ are linear functions of their arguments. Let

$$W_t^U(\mathbf{k}_{U,t-1}, z_{t-1}) = P_t^U + \sum_{i\in U} q_{i,t}^U k_{i,t-1} + R_t^U z_{t-1}$$

and

$$w_{i,t}^U(k_{i,t-1}, z_{t-1}) = p_{i,t}^U + q_{i,t}^U k_{i,t-1} + r_{i,t}^U z_{t-1}, \quad \forall i \notin U$$

where the parameters $P_t^U, q_{i,t}^U, R_t^U (i \in U, t \in \mathcal{T})$ and $p_{i,t}^U, q_{i,t}^U, r_{i,t}^U (i \notin U,\ t \in \mathcal{T})$ are to be identified.

Assume that $\mathbf{k}_{\mathcal{N},t}^U$ and $\mathbf{e}_{\mathcal{N},t}^U$ are the solution of the FOC characterizing the PAFE_U$_t$. From (43) and (44), it follows that:

$$P_t^U + \sum_{i\in U} q_{i,t}^U k_{i,t-1} + R_t^U z_{t-1} = \sum_{i\in U} \left[F_i(k_{i,t}^U, e_{i,t}^U) - k_{i,t}^U + [1-\delta_i]k_{i,t-1} - \pi_i z_t^U \right.$$
$$+ \rho \left[p_{i,t+1}^v + q_{i,t+1}^v k_{i,t}^U + r_{i,t+1}^v z_t^U\right] + \rho \frac{\pi_i}{\pi_{\mathcal{N}}} \left[P_{t+1}^{\mathcal{N}} + \sum_{j\in\mathcal{N}} q_{j,t+1}^{\mathcal{N}} k_{j,t}^U + R_{t+1}^{\mathcal{N}} z_t^U \right.$$
$$\left.\left. - \sum_{j\in\mathcal{N}} \left[p_{j,t+1}^v + q_{j,t+1}^v k_{j,t}^U + r_{j,t+1}^v z_t^U\right] \right]\right] \quad (45)$$

and

$$p_{i,t}^U + q_{i,t}^U k_{i,t-1} + r_{i,t}^U z_{t-1} = \left[F_i(k_{i,t}^U, e_{i,t}^U) - k_{i,t}^U + [1-\delta_i]k_{i,t-1} - \pi_i z_t^U \right.$$
$$+ \rho \left[p_{i,t+1}^v + q_{i,t+1}^v k_{i,t}^U + r_{i,t+1}^v z_t^U\right] + \rho \frac{\pi_i}{\pi_{\mathcal{N}}} \left[P_{t+1}^{\mathcal{N}} + \sum_{i\in\mathcal{N}} q_{i,t+1}^{\mathcal{N}} k_{i,t}^U + R_{t+1}^{\mathcal{N}} z_t^U \right.$$
$$\left.\left. - \sum_{j\in\mathcal{N}} \left[p_{j,t+1}^v + q_{j,t+1}^v k_{i,t}^U + r_{j,t+1}^v z_t^U\right] \right]\right], \quad i \notin U \quad (46)$$

[6] Clearly, for $U = \mathcal{N}$, the expression (44) disappears as well as those derived from it in the sequel.

where $z_t^U = [1-\gamma]z_{t-1} + E_t^U$ and $E_t^U =_{def} \sum_{i=1}^n e_{i,t}^U$. The parameter identification in the two members of (45) gives:

$$P_t^U = \sum_{i\in U}\left[F_i(k_{i,t}^U, e_{i,t}^U) - k_{i,t}^U - \pi_i E_t^U + \rho\left[p_{i,t+1}^v + q_{i,t+1}^v k_{i,t}^U + r_{i,t+1}^v E_t^U\right]\right.$$
$$\left. + \rho\frac{\pi_i}{\pi_{\mathcal{N}}}\left[P_{t+1}^{\mathcal{N}} + \sum_{j\in\mathcal{N}} q_{j,t+1}^{\mathcal{N}} k_{j,t}^U + R_{t+1}^{\mathcal{N}} E_t^U - \sum_{j\in\mathcal{N}}\left[p_{j,t+1}^v + q_{j,t+1}^v k_{j,t}^U + r_{j,t+1}^v E_t^U\right]\right]\right] \quad (47)$$

$$q_{i,t}^U = 1 - \delta_i, \quad i \in U \quad (48)$$

$$R_t^U = [1-\gamma]\sum_{i\in U}\left[-\pi_i + \rho r_{i,t+1}^v + \rho\frac{\pi_i}{\pi_{\mathcal{N}}}\left[R_{t+1}^{\mathcal{N}} - \sum_{j\in\mathcal{N}} r_{j,t+1}^v\right]\right]. \quad (49)$$

Similarly, the identification in the two members of (46) gives:

$$p_{it}^U = \left[F_i(k_{i,t}^U, e_{i,t}^U) - k_{i,t}^U - \pi_i E_t^U\right.$$
$$+ \rho\left[p_{i,t+1}^v + q_{i,t+1}^v k_{i,t}^U + r_{i,t+1}^v E_t^U\right] + \rho\frac{\pi_i}{\pi_{\mathcal{N}}}\left[P_{t+1}^{\mathcal{N}} + \sum_{j\in\mathcal{N}} q_{j,t+1}^{\mathcal{N}} k_{j,t}^U + R_{t+1}^{\mathcal{N}} E_t^U\right.$$
$$\left.\left. - \sum_{j\in\mathcal{N}}\left[p_{j,t+1}^v + q_{j,t+1}^v k_{j,t}^U + r_{j,t+1}^v E_t^U\right]\right]\right], \quad i \notin U \quad (50)$$

$$q_{i,t}^U = 1 - \delta_i, \quad i \notin U \quad (51)$$

$$r_{it}^U = [1-\gamma]\left[-\pi_i + \rho r_{i,t+1}^v + \rho\frac{\pi_i}{\pi_{\mathcal{N}}}\left[R_{t+1}^{\mathcal{N}} - \sum_{j\in\mathcal{N}} r_{j,t+1}^v\right]\right], \quad i \notin U. \quad (52)$$

Finally, the FOC derived from (43) and (44) lead to the following equations:

$$\frac{\partial F_i}{\partial k_{i,t}}(k_{i,t}^U, e_{i,t}^U) = 1 - \rho q_{i,t+1}^v - \rho\left[q_{i,t+1}^{\mathcal{N}} - q_{i,t+1}^v\right]\sum_{j\in U}\frac{\pi_j}{\pi_{\mathcal{N}}}, \quad i \in U \quad (53)$$

$$\frac{\partial F_i}{\partial k_{i,t}}(k_{i,t}^U, e_{i,t}^U) = 1 - \rho q_{i,t+1}^v - \rho\left[q_{i,t+1}^{\mathcal{N}} - q_{i,t+1}^v\right]\frac{\pi_i}{\pi_{\mathcal{N}}}, \quad i \notin U \quad (54)$$

$$\frac{\partial F_i}{\partial e_{i,t}}(k_{i,t}^U, e_{i,t}^U) = \sum_{j\in U}\left[\pi_j - \rho r_{j,t+1}^v + \rho\frac{\pi_j}{\pi_{\mathcal{N}}}\left[R_{t+1}^{\mathcal{N}} - \sum_{l\in\mathcal{N}} r_{l,t+1}^v\right]\right], \quad i \in U \quad (55)$$

$$\frac{\partial F_i}{\partial e_{i,t}}(k_{i,t}^U, e_{i,t}^U) = \pi_i - \rho r_{i,t+1}^v + \rho\frac{\pi_i}{\pi_{\mathcal{N}}}\left[R_{t+1}^{\mathcal{N}} - \sum_{j\in\mathcal{N}} r_{j,t+1}^v\right], \quad i \notin U \quad (56)$$

Eqs. (47)–(56) form a system of equations whose unknowns are $\{(P_t^U, q_{i,t}^U(i \in U), R_t^U), (p_{it}^U, q_{i,t}^U, r_{it}^U; i \notin U), (k_{i,t}^U, e_{i,t}^U; i \in \mathcal{N}); t \in \mathcal{T}\}$ where all variables are nil when $t = T+1$.

3.2. *Solving the system*

3.2.1. $q_{i,t}^U, i \in \mathcal{N}, t \in \mathcal{T}$

These parameters are immediately known via (48) and (51).

3.2.2. R_t^U and $r_{it}^U (i \notin U)$, $t \in \mathcal{T}$

First one observes that in the particular case $U = \mathcal{N}$, (49) leads to $R_t^{\mathcal{N}} = [1-\gamma][-\pi_{\mathcal{N}} + \rho R_{t+1}^{\mathcal{N}}]$ (recall that $\pi_{\mathcal{N}} = \sum_{j\in\mathcal{N}} \pi_j$). On the other hand, when $U = v$, $r_{i,t}^v = [1-\gamma][-\pi_i + \rho r_{i,t+1}^v + \rho \frac{\pi_i}{\pi_{\mathcal{N}}}[R_{t+1}^{\mathcal{N}} - \sum_{j\in\mathcal{N}} r_{i,t+1}^v]] \Rightarrow \sum_{i\in U} r_{i,t}^v = R_t^U, \forall U \subset \mathcal{N}$. This is particular true for $U = \mathcal{N}$. Then (49) reduces to:
(i) coalition U:

$$R_t^U = [1-\gamma]\left[-\pi_U + \rho R_{t+1}^U\right]$$

where $\pi_U =_{def} \sum_{i\in U} \pi_i$. Given that $R_{T+1}^U = 0$, it follows that:

$$R_t^U = -\pi_U[1-\gamma]\frac{1-\rho^{T+1-t}[1-\gamma]^{T+1-t}}{1-\rho[1-\gamma]}, \quad U \subset \mathcal{N}. \tag{57}$$

When $U = v$,

$$r_{i,t}^v = -\pi_i[1-\gamma]\frac{1-\rho^{T+1-t}[1-\gamma]^{T+1-t}}{1-\rho[1-\gamma]}, \quad i \in \mathcal{N}. \tag{58}$$

(ii) For non-members of the coalition, it follows that $r_{it}^U = [1-\gamma]\left[-\pi_i + \rho r_{i,t+1}^v\right] \Rightarrow r_{it}^U = r_{i,t}^v (i \notin U)$.

3.2.3. $k_{i,t}^U$ and $e_{i,t}^U$, $i \in \mathcal{N}$, $t \in \mathcal{T}$

FOC (53)–(56) reduce to:

$$\frac{\partial F_i}{\partial k_{i,t}}(k_{i,t}^U, e_{i,t}^U) = 1 - \rho\,[1-\delta_i], \quad i \in \mathcal{N} \tag{59}$$

$$\frac{\partial F_i}{\partial e_{i,t}}(k_{i,t}^U, e_{i,t}^U) = \pi_U - \rho R_t^U, \quad i \in U \tag{60}$$

$$\frac{\partial F_i}{\partial e_{i,t}}(k_{i,t}^U, e_{i,t}^U) = \pi_i - \rho r_{i,t}^v, \quad i \notin U. \tag{61}$$

Given that R_t^U and $r_{i,t}^v$ are known via (57) and (58), this system enables one to compute the solutions $\mathbf{k}_{\mathcal{N},t}^U$ and $\mathbf{e}_{\mathcal{N},t}^U$.

For example, if F_i is the familiar Cobb–Douglas production function defined by $y_i = F_i(k,e) = k^{\alpha_i} e^{\beta_i}$ (with $0 < \alpha_i, \beta_i < \alpha_i + \beta_i < 1$), then:

$$k_{i,t}^U = \left[\frac{1-\rho[1-\delta_i]}{\alpha_i}\right]^{[1-\beta_i]/[\alpha_i+\beta_i-1]} \left[\frac{\pi_U\{1-[\rho[1-\gamma]]^{T+1-t}\}}{\beta_i[1-\rho[1-\gamma]]}\right]^{\beta_i/[\alpha_i+\beta_i-1]}$$

$$e_{i,t}^U = \left[\frac{1-\rho[1-\delta_i]}{\alpha_i}\right]^{\alpha_i/[\alpha_i+\beta_i-1]} \left[\frac{\pi_U\{1-[\rho[1-\gamma]]^{T+1-t}\}}{\beta_i[1-\rho[1-\gamma]]}\right]^{[1-\alpha_i]/[\alpha_i+\beta_i-1]}$$

$$y_{i,t}^U = (k_{i,t}^U)^{\alpha_i}(e_{i,t}^U)^{\beta_i} = \left[\frac{1-\rho[1-\delta_i]}{\alpha_i}\right]^{\alpha_i/[\alpha_i+\beta_i-1]} \left[\frac{\pi_U\{1-[\rho[1-\gamma]]^{T+1-t}\}}{\beta_i[1-\rho[1-\gamma]]}\right]^{\beta_i/[\alpha_i+\beta_i-1]}.$$

3.2.4. P_t^U and $p_{it}^U (i \notin U)$, $t \in \mathcal{T}$

(47) reduces to:

$$P_t^U = \sum_{i\in U}\left[F_i(k_{i,t}^U, e_{i,t}^U) - k_{i,t}^U - \pi_i E_t^U + \rho\left[p_{i,t+1}^v + [1-\delta_i]\,k_{i,t}^U + r_{i,t+1}^v E_t^U + \frac{\pi_i}{\pi_{\mathcal{N}}}\left[P_{t+1}^{\mathcal{N}} - \sum_{j\in\mathcal{N}} p_{j,t+1}^v\right]\right]\right].$$

Thus

$$P_t^{\mathcal{N}} = \sum_{i \in N} \left[F_i(k_{i,t}^{\mathcal{N}}, e_{i,t}^{\mathcal{N}}) - k_{i,t}^{\mathcal{N}}\right] - \pi_N E_t^{\mathcal{N}} + \rho \left[P_{t+1}^{\mathcal{N}} + \sum_{i \in \mathcal{N}} [1-\delta_i]\, k_{i,t}^{\mathcal{N}} + R_{t+1}^{\mathcal{N}} E_t^{\mathcal{N}}\right]$$
$$= \sum_{\tau=t}^{T} \rho^{\tau - t} \left[\sum_{i \in N} \left[F_i(k_{i,\tau}^{\mathcal{N}}, e_{i,\tau}^{\mathcal{N}}) - k_{i,\tau}^{\mathcal{N}} + \rho\, [1-\delta_i]\, k_{i,\tau}^{\mathcal{N}} + \rho R_{\tau+1}^{\mathcal{N}} E_\tau^{\mathcal{N}}\right] - \pi_{\mathcal{N}} E_\tau^{\mathcal{N}}\right]. \tag{62}$$

When $U = v$,

$$p_{it}^{v} = F_i(k_{i,t}^{v}, e_{i,t}^{v}) - k_{i,t}^{v} - \pi_i E_t^{v} + \rho \left[p_{i,t+1}^{v} + [1-\delta_i]\, k_{i,t}^{v} + r_{i,t+1}^{v} E_t^{v} + \frac{\pi_i}{\pi_{\mathcal{N}}}\left[P_{t+1}^{\mathcal{N}} - \sum_{j \in \mathcal{N}} p_{i,t+1}^{v}\right]\right] \tag{63}$$

for all $i \in \mathcal{N}$. Summing on i gives:

$$\sum_{i \in \mathcal{N}} p_{it}^{v} = \sum_{i \in \mathcal{N}} \left[F_i(k_{i,t}^{v}, e_{i,t}^{v}) - k_{i,t}^{v}\right] - \pi_{\mathcal{N}} E_t^{v} + \rho \left[P_{t+1}^{\mathcal{N}} + \sum_{i \in \mathcal{N}} [1-\delta_i]\, k_{i,t}^{v} + \sum_{i \in \mathcal{N}} r_{i,t+1}^{v} E_t^{v}\right] \tag{64}$$

(62) and (64) give:

$$P_t^{\mathcal{N}} - \sum_{j \in \mathcal{N}} p_{j,t}^{v} = \sum_{i=1}^{n} \left[\Delta F_i - \Delta k_{i,t}\right] - \pi_{\mathcal{N}} \Delta E_t + \rho \left[\sum_{i=1}^{n} [1-\delta_i]\, \Delta k_{i,t} - R_{t+1}^{\mathcal{N}} \Delta E_t\right] \tag{65}$$

where by definition $\Delta x_t = x_t^{\mathcal{N}} - x_t^{v}$ is the difference between the values of x_t at the IO_t (where $U = \mathcal{N}$) and at the fallback non-cooperative equilibrium (where $U = v$). From the previous computations, all the quantities of the RHS are known so that $P_t^{\mathcal{N}} - \sum_{j \in \mathcal{N}} p_{j,t}^{v}$ is computable. Then $p_{i,t}$ $(\forall i)$ follows as well from the integration of (63):

$$p_{it}^{v} = \sum_{\tau=t}^{T} \rho^{\tau - t} \left[F_i(k_{i,\tau}^{v}, e_{i,\tau}^{v}) - k_{i,\tau}^{v} - \pi_i E_\tau^{v} + \rho \left[[1-\delta_i]\, k_{i,\tau}^{v} + r_{i,\tau+1}^{v} E_t^{v} + \frac{\pi_i}{\pi_{\mathcal{N}}}\left[P_{\tau+1}^{\mathcal{N}} - \sum_{j \in \mathcal{N}} p_{\tau,t+1}^{v}\right]\right]\right]$$

and the whole system is solved.

In the infinite horizon case, the solution is obtained by taking the limit $T \to +\infty$ in the solutions (57)–(65). Then one easily verifies that all the parameters and control variables $\{(P_t^U, q_{i,t}^U (i \in U), R_t^U), (p_{it}^U, q_{i,t}^U, r_{it}^U; i \notin U), (k_{i,t}^U, e_{i,t}^U; i \in \mathcal{N}); t \in \mathcal{T}\}$ are constant at all periods. Starting from its initial value, the stock of pollutant increases or decreases monotonically to an asymptotic constant value.

4. Coalitional rationality

Assume that at date t there exists a sequence of future transfers that makes international cooperation rational in the sense of coalitions from $t + 1$ onwards. Let $\mathbf{k}_t^{\mathcal{N}}$ and $z_t^{\mathcal{N}}$ be the vector of capital stocks and the stock of pollution at the international optimum at date t. Let $\mathbf{k}_t^{v}$ and z_t^{v} be the vector of capital stocks and the stock of pollution at the fallback non-cooperative equilibrium at date t. Let $(w_{1t}^{\mathcal{N}}, \ldots, w_{nt}^{\mathcal{N}})$ and $(w_{1t}^{v}, \ldots, w_{nt}^{v})$ be the vectors of the countries' payoffs at the IO *without current transfers* and at the fallback non-cooperative equilibrium at date t respectively. Let $W_t^{\mathcal{N}}$ and W_t^{v} be the sum of the components of these vectors. Let the vector of countries' payoffs *with current transfers* $(\widetilde{w}_{1,t}^{\mathcal{N}}, \ldots, \widetilde{w}_{n,t}^{\mathcal{N}})$ be defined by

$$\widetilde{w}_{i,t}^{\mathcal{N}}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}) = w_{i,t}^{\mathcal{N}}(k_{i,t-1}, z_{t-1}) + \theta_{i,t}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}), \quad i \in \mathcal{N}$$

where the vector of current transfers $(\theta_{1t}, \ldots, \theta_{nt})$ is such that

$$\theta_{i,t}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}) = -[w_{i,t}^{\mathcal{N}}(k_{i,t-1}, z_{t-1}) - w_{i,t}^{v}(k_{i,t-1}, z_{t-1})] + \frac{\pi_i}{\pi_{\mathcal{N}}}[W_t^{\mathcal{N}}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}) - W_t^{v}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1})]. \tag{66}$$

Theorem. *With the transfers (66), one has for every coalition $U \subset \mathcal{N}$:*

$$\sum_{i \in U} \widetilde{w}_{i,t}^{\mathcal{N}}(k_{i,t-1}, z_{t-1}) \geq \sum_{i \in U} w_{i,t}^{U}(k_{i,t-1}, z_{t-1}) = W_t^{U}(\mathbf{k}_{U,t-1}, z_{t-1}) \tag{67}$$

that is, the vector $(\widetilde{w}_{i,t}^{\mathcal{N}}, i \in \mathcal{N})$ has the core property (42).

Thus the IO_t with transfers (66) make international cooperation rational in the sense of coalitions at every date t as announced at the end of Section 2.

Proof of the theorem. The proof makes use of the 3 following lemmas.

Lemma 1. *The transfers (66) can be rewritten:*

$$\theta_{it}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}) = -\left[y_{i,t}^{\mathcal{N}} - y_{i,t}^{v} - [1 - \rho\,[1 - \delta_i]]\left[k_{i,t}^{\mathcal{N}} - k_{i,t}^{v}\right]\right] + \frac{\pi_i}{\pi_{\mathcal{N}}} \sum_{j=1}^{n} \left[y_{j,t}^{\mathcal{N}} - y_{j,t}^{v} - \left[1 - \rho\left[1 - \delta_j\right]\right]\left[k_{j,t}^{\mathcal{N}} - k_{j,t}^{v}\right]\right].$$

Proof. Recall that $W_t^{\mathcal{N}}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}) = P_t^{\mathcal{N}} + \sum_{i \in \mathcal{N}} q_{i,t}^{\mathcal{N}} k_{i,t-1} + R_t^{\mathcal{N}} z_{t-1}$ and $W_t^{v}(\mathbf{k}_{t-1}, z_{t-1}) = \sum_{i=1}^{n} w_{i,t}^{v}(k_{i,t-1}, z_{t-1}) = \sum_{i=1}^{n}\left[p_{i,t}^{v} + q_{i,t}^{v} k_{i,t-1} + r_{i,t}^{v} z_{t-1}\right]$. Recall that $q_{i,t}^{\mathcal{N}} = q_{i,t}^{v}$ and $R_t^{\mathcal{N}} = \sum_{i=1}^{n} r_{i,t}^{v}$ (see Section 3). It follows that

$$\theta_{i,t}(\mathbf{k}_{t-1}, z_{t-1}) = -[w_{i,t}^{\mathcal{N}}(k_{i,t-1}, z_{t-1}) - w_{i,t}^{v}(k_{i,t-1}, z_{t-1})] + \frac{\pi_i}{\pi_{\mathcal{N}}}\left[P_t^{\mathcal{N}} - \sum_{i=1}^{n} p_{i,t}^{v}\right]. \tag{68}$$

Now:

$$\begin{aligned} w_{i,t}^{\mathcal{N}}(k_{i,t-1}, z_{t-1}) &= y_{i,t}^{\mathcal{N}} - k_{i,t}^{\mathcal{N}} + [1 - \delta_i]k_{i,t-1} - \pi_i z_t^{\mathcal{N}} + \rho[w_{i,t+1}^{v}(k_{i,t}^{\mathcal{N}}, z_t^{\mathcal{N}})] \\ &\quad + \frac{\pi_i}{\pi_{\mathcal{N}}}\left[W_{t+1}^{\mathcal{N}}(\mathbf{k}_{\mathcal{N},t}^{\mathcal{N}}, z_t^{\mathcal{N}}) - W_{t+1}^{v}(\mathbf{k}_{\mathcal{N},t}^{\mathcal{N}}, z_t^{\mathcal{N}})\right] \\ &= y_{i,t}^{\mathcal{N}} - k_{i,t}^{\mathcal{N}} + [1 - \delta_i]k_{i,t-1} - \pi_i z_t^{\mathcal{N}} + \rho\left[p_{i,t+1}^{v} + q_{i,t+1}^{v} k_{i,t}^{\mathcal{N}} + r_{i,t+1}^{v} z_t^{\mathcal{N}}\right. \\ &\quad \left. + \frac{\pi_i}{\pi_{\mathcal{N}}}\left[P_{t+1}^{\mathcal{N}} - \sum_{i=1}^{n} p_{i,t+1}^{v}\right]\right] \end{aligned}$$

Similarly,

$$\begin{aligned} w_{i,t}^{v}(k_{i,t-1}, z_{t-1}) &= y_{i,t}^{v} - k_{i,t}^{v} + [1 - \delta_i]k_{i,t-1} - \pi_i z_t^{v} + \rho[w_{i,t+1}^{v}(k_{i,t}^{v}, z_t^{v}) \\ &\quad + \frac{\pi_i}{\pi_{\mathcal{N}}}[W_{t+1}^{\mathcal{N}}(\mathbf{k}_{\mathcal{N},t}^{v}, z_t^{v}) - W_{t+1}^{v}(\mathbf{k}_{\mathcal{N},t}^{v}, z_t^{v})]] \\ &= y_{i,t}^{v} - k_{i,t}^{v} + [1 - \delta_i]k_{i,t-1} - \pi_i z_t^{v} + \rho\left[p_{i,t+1}^{v} + q_{i,t+1}^{v} k_{i,t}^{v} + r_{i,t+1}^{v} z_t^{v}\right. \\ &\quad \left. + \frac{\pi_i}{\pi_{\mathcal{N}}}\left[P_{t+1}^{\mathcal{N}} - \sum_{i=1}^{n} p_{i,t+1}^{v}\right]\right]. \end{aligned}$$

Thus, making use of the solution for $q^{v}_{i,t+1}$ and $r^{v}_{i,t+1}$ (recall (48), (51) and (58)), of $z^{v}_{t} = [1-\gamma]z_{t-1}+E^{v}_{t}$ and of $z^{\mathcal{N}}_{t} = [1-\gamma]z_{t-1}+E^{\mathcal{N}}_{t}$,

$$w^{\mathcal{N}}_{i,t}(k_{i,t-1}, z_{t-1}) - w^{v}_{i,t}(k_{i,t-1}, z_{t-1}) = y^{\mathcal{N}}_{i,t} - y^{v}_{i,t} - [1-\rho\,[1-\delta_i]]\left[k^{\mathcal{N}}_{i,t} - k^{v}_{i,t}\right] + \pi_i\left[E^{\mathcal{N}}_{t} - E^{v}_{t}\right] - \pi_i[1-\gamma]\frac{1-\rho^{T-t}[1-\gamma]^{T-t}}{1-\rho[1-\gamma]}\left[E^{\mathcal{N}}_{t} - E^{v}_{t}\right].$$

On the other hand, given (65):

$$P^{\mathcal{N}}_{t+1} - \sum_{i=1}^{n} p^{v}_{i,t+1} = \sum_{i=1}^{n}\left[y^{\mathcal{N}}_{i,t} - y^{v}_{i,t} - \left[k^{\mathcal{N}}_{i,t} - k^{v}_{i,t}\right] - \pi_i\left[E^{\mathcal{N}}_{t} - E^{v}_{t}\right]\right] + \rho\left[\sum_{i=1}^{n}[1-\delta_i]\left[k^{\mathcal{N}}_{i,t} - k^{v}_{i,t}\right] - \pi_{\mathcal{N}}[1-\gamma]\frac{1-\rho^{T-t}[1-\gamma]^{T-t}}{1-\rho[1-\gamma]}\left[E^{\mathcal{N}}_{t} - E^{v}_{t}\right]\right].$$

Putting these two last expressions in (68) completes the proof. ■

Lemma 2. *At date t, comparing the fallback non-cooperative equilibrium and the PAFE_U, one has*

$$\text{(a) } y^{U}_{i,t} - [1-\rho\,[1-\delta_i]]\,k^{U}_{i,t} > y^{v}_{i,t} - [1-\rho\,[1-\delta_i]]\,k^{v}_{i,t}, \quad i \in U \tag{69}$$

$$\text{(b) } y^{U}_{i,t} - [1-\rho\,[1-\delta_i]]\,k^{U}_{i,t} = y^{v}_{i,t} - [1-\rho\,[1-\delta_i]]\,k^{v}_{i,t}, \quad i \notin U. \tag{70}$$

Proof. (i) The FOC characterizing the PAFE_U$_t$ are:

$$\frac{\partial F_i}{\partial k_{i,t}}(k^{U}_{i,t}, e^{U}_{i,t}) = 1-\rho\,[1-\delta_i] =_{def} \mu_i \tag{71}$$

$$\frac{\partial F_i}{\partial e_{i,t}}(k^{U}_{i,t}, e^{U}_{i,t}) = \pi\left[1+\rho[1-\gamma]\frac{1-\rho^{T-t}[1-\gamma]^{T-t}}{1-\rho[1-\gamma]}\right] =_{def} \pi\,\eta_t \tag{72}$$

with

$\pi = \pi_U$ if $i \in U$
$\pi = \pi_i$ if $i \notin U$.

One observes that the FOC are the same at the FNCE$_t$ and at the PAFE_U$_t$ for $i \notin U$, so that $k^{U}_{i,t} = k^{v}_{i,t}$ and $e^{U}_{i,t} = e^{v}_{i,t} \Rightarrow y^{U}_{i,t} = y^{v}_{i,t} (i \notin U)$. Thus (b) is proved.

(ii) Let us differentiate totally (71) and (72) w.r.t. π:

$$\frac{\partial^2 F_i}{\partial k^2_{i,t}}\mathrm{d}k_{i,t} + \frac{\partial^2 F_i}{\partial k_{i,t}\partial e_{i,t}}\mathrm{d}e_{i,t} = 0 \tag{73}$$

$$\frac{\partial^2 F_i}{\partial k_{i,t}\partial e_{i,t}}\mathrm{d}k_{i,t} + \frac{\partial^2 F_i}{\partial e^2_{i,t}}\mathrm{d}e_{i,t} = \eta_t \mathrm{d}\pi. \tag{74}$$

Solving the system leads to:

$$\mathrm{d}e_{i,t} = \frac{\frac{\partial^2 F_i}{\partial k^2_{i,t}}}{\frac{\partial^2 F_i}{\partial k^2_{i,t}}\frac{\partial^2 F_i}{\partial e^2_{i,t}} - \left[\frac{\partial^2 F_i}{\partial k_{i,t}\partial e_{i,t}}\right]^2}\mathrm{d}\pi =_{def} \Delta_i \mathrm{d}\pi \tag{75}$$

$\Delta_i < 0$ because of the assumptions on F_i (see Section 1). On the other hand, $y_{i,t} = F_i(k_{i,t}, e_{i,t}) \Rightarrow$

$$dy_{i,t} = \frac{\partial F_i}{\partial k_{i,t}}\mathrm{d}k_{i,t} + \frac{\partial F_i}{\partial e_{i,t}}\mathrm{d}e_{i,t}. \tag{76}$$

Given (71) and (75), one has at the PAFE_U$_t$:

$$dy_{i,t} - \mu_i \mathrm{d}k_{i,t} = \frac{\partial F_i}{\partial e_{i,t}} \eta_t \mathrm{d}\pi < 0 \quad \text{if } \mathrm{d}\pi > 0 \tag{77}$$

because of the assumptions on F_i (see Section 1) and $\eta_t > 0$.

For coalition members, moving from the FNCE$_t$ to the PAFE_U$_t$ can be seen as a succession of small increments $\mathrm{d}\pi$, starting at π_i an finishing at $\pi_U = \sum_{i \in U} \pi_i \, (> \pi_i)$. So that point (a) follows. ■

Lemma 3. *if* $\exists U \subset \mathcal{N}$ *such that:*

$$W_t^U(\mathbf{k}_{U,t-1}, z_{t-1}) > \sum_{i \in U} \widetilde{w}_{it}^{\mathcal{N}}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}) \tag{78}$$

then the vector $(\widehat{w}_{1t}, \ldots, \widehat{w}_{nt})$ *defined by*

$$\widehat{w}_{it}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}) = w_{it}^{\mathcal{N}}(k_{i,t-1}, z_{t-1}) + \widehat{\theta}_{it}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}), \quad i \in \mathcal{N} \tag{79}$$

$$\text{where } \widehat{\theta}_{it}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}) = -[w_{it}^{\mathcal{N}}(k_{i,t-1}, z_{t-1}) - w_{it}^{U}(k_{i,t-1}, z_{t-1})] + \frac{\pi_i}{\pi_{\mathcal{N}}}\left[W_t^{\mathcal{N}}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}) - \sum_{j=1}^{n} w_{it}^U(k_{i,t-1}, z_{t-1})\right] \tag{80}$$

$$\begin{aligned} \text{where } w_{it}^U(k_{i,t-1}, z_{t-1}) &= F_i(k_{i,t}^U, e_{i,t}^U) - k_{i,t}^U + [1-\delta_i]k_{i,t-1} - \pi_i[[1-\gamma]z_{t-1} + E_t^U] \\ &+ \rho w_{i,t+1}^{v}\left(k_{i,t}^U, [1-\gamma]z_{t-1} + E_t^U\right) \\ &+ \rho \frac{\pi_i}{\pi_{\mathcal{N}}}\left[W_{t+1}^{\mathcal{N}}(\mathbf{k}_{\mathcal{N},t}^U, [1-\gamma]z_{t-1} + E_t^U) - W_{t+1}^{v}(\mathbf{k}_{\mathcal{N},t}^U, [1-\gamma]z_{t-1} + E_t^U)\right] \end{aligned} \tag{81}$$

dominates $(\widetilde{w}_{1t}^{\mathcal{N}}, \ldots, \widetilde{w}_{nt}^{\mathcal{N}})$ *in the sense that*

$$\text{(i)} \quad \sum_{i \in U} \widehat{w}_{it}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}) > \sum_{i \in U} \widetilde{w}_{it}^{\mathcal{N}}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}) \tag{82}$$

$$\text{(ii)} \quad \widehat{w}_{it}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}) \geq \widetilde{w}_{it}^{\mathcal{N}}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}), \quad i \notin U. \tag{83}$$

Proof. (i) (79) et (80) ⇒

$$\begin{aligned} \widehat{w}_{it}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}) &= w_{it}^U(k_{i,t-1}, z_{t-1}) + \frac{\pi_i}{\pi_{\mathcal{N}}}\left[W_t^{\mathcal{N}}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}) - \sum_{j=1}^{n} w_{it}^U(k_{i,t-1}, z_{t-1})\right] \\ &\geq w_{it}^U(k_{i,t-1}, z_{t-1}) \end{aligned} \tag{84}$$

because the term between brackets is necessarily positive by definition of the IO. Then

$$\sum_{i \in U} \widehat{w}_{it}(\mathbf{k}_{t-1}, z_{t-1}) \geq \sum_{i \in U} w_{it}^U(k_{i,t-1}, z_{t-1}) = W_t^U(\mathbf{k}_{U,t-1}, z_{t-1}) > \sum_{i \in U} \widetilde{w}_{it}^{\mathcal{N}}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1})$$

where the first inequality results from (84) and the second follows from assumption (78). Thus (82) is verified.

(ii) (83) can be rewritten

$$\begin{aligned} \widehat{w}_{it}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}) &= w_{it}^{\mathcal{N}}(k_{i,t-1}, z_{t-1}) + \widehat{\theta}_{it}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}) \\ &\geq \widetilde{w}_{it}^{\mathcal{N}}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}) = w_{it}^{\mathcal{N}}(k_{i,t-1}, z_{t-1}) + \theta_{it}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}), \quad i \notin U. \end{aligned}$$

Thus verifying (83) is equivalent to verity that

$$\widehat{\theta}_{it}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}) \geq \theta_{it}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}), \quad i \notin U.$$

Now, by Lemma 1,

$$\theta_{it}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}) = -\left[y^{\mathcal{N}}_{i,t} - y^{v}_{i,t} - [1-\rho[1-\delta_i]]\left[k^{\mathcal{N}}_{i,t} - k^{v}_{i,t}\right]\right] + \frac{\pi_i}{\pi_{\mathcal{N}}}\sum_{j=1}^{n}\left[y^{\mathcal{N}}_{j,t} - y^{v}_{j,t} - \left[1-\rho\left[1-\delta_j\right]\right]\left[k^{\mathcal{N}}_{j,t} - k^{v}_{j,t}\right]\right].$$

By a similar reasoning,

$$\widehat{\theta}_{it}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}) = -\left[y^{\mathcal{N}}_{i,t} - y^{U}_{i,t} - [1-\rho[1-\delta_i]]\left[k^{\mathcal{N}}_{i,t} - k^{U}_{i,t}\right]\right] + \frac{\pi_i}{\pi_{\mathcal{N}}}\sum_{j=1}^{n}\left[y^{\mathcal{N}}_{j,t} - y^{U}_{j,t} - \left[1-\rho\left[1-\delta_j\right]\right]\left[k^{\mathcal{N}}_{j,t} - k^{U}_{j,t}\right]\right].$$

Then

$$\widehat{\theta}_{it}(\mathbf{k}_{t-1}, z_{t-1}) \geq \theta_{it}(\mathbf{k}_{t-1}, z_{t-1})(i \notin U) \Rightarrow -\left[y^{U}_{i,t} - y^{v}_{i,t} - [1-\rho[1-\delta_i]]\left[k^{U}_{i,t} - k^{v}_{i,t}\right]\right] + \frac{\pi_i}{\pi_{\mathcal{N}}}\sum_{j=1}^{n}\left[y^{U}_{j,t} - y^{v}_{j,t} - \left[1-\rho\left[1-\delta_j\right]\right]\left[k^{U}_{j,t} - k^{v}_{j,t}\right]\right] \geq 0, \quad i \notin U.$$

This is indeed true because of Lemma 2, so (83) is verified. ■

Proof of the theorem. (82) and (83) ⇒

$$\sum_{i=1}^{n}\widehat{w}_{it}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}) > \sum_{i=1}^{n}\widetilde{w}^{\mathcal{N}}_{it}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1})$$

$$\Rightarrow \sum_{i=1}^{n}\left[w^{\mathcal{N}}_{it}(k_{i,t-1}, z_{t-1}) + \widehat{\theta}_{it}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1})\right]$$

$$> \sum_{i=1}^{n}\left[w^{\mathcal{N}}_{it}(k_{i,t-1}, z_{t-1}) + \theta_{it}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1})\right] \tag{85}$$

$$\Rightarrow \sum_{i=1}^{n}\widehat{\theta}_{it}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}) > \sum_{i=1}^{n}\theta_{it}(\mathbf{k}_{\mathcal{N},t-1}, z_{t-1}). \tag{86}$$

Now this last result is impossible because these two sums are by construction equal to 0. This contradicts the thesis of Lemma 3, so the theorem is demonstrated. ■

5. Conclusion

What can be learned from the above extension to a two-dimensional setting of the Germain et al. (1998a,b, 2003) dynamic model of international environmental agreements? There are two aspects. From the point of view of economic modeling, the inclusion of investment and capital accumulation increases the realism of the model. Explicit analytical solutions have been obtained for both the environmental and the economic variables, showing the influence of emissions abatement on the capital accumulation process. In this respect, the assumption of linearity of the damage functions is however an important limitation. Assuming convexity might shed more light on this relation, but it requires further analytical work. The key issue is that control variables are no more independent of the inherited stocks. Yet the solutions currently available may serve as benchmarks in evaluating integrated assessment simulation models of the general equilibrium type. From the game-theoretic point of view, we observe that capital accumulation does not modify in an essential way the strategic nature of the problem: typically the capital and investment variables do not enter the equations that determine the transfers. This is due to the fact that strategic factors arise from the international externality only and not from the capital accumulation, which in this model has domestic impacts only.

References

Chander, P., Tulkens, H., 1992. Theoretical foundations of negotiations and cost sharing in transfrontier pollution problems. European Economic Review 36 (2/3), 288–299.
Chander, P., Tulkens, H., 1995. A core-theoretic solution for the design of cooperative agreements on transfrontier pollution. International Tax and Public Finance 2, 279–293.
Chander, P., Tulkens, H., 1997. The core of an economy with multilateral environmental externalities. International Journal of Game Theory 26, 379–401.
d'Aspremont, C., Jaskold Gabszewicz, J., 1986. On the stability of collusion. In: Stiglitz, J.E., Mathewson, G.F. (Eds.), New Developments in the Analysis of Market Structure. The MIT Press, Cambridge, Mass, pp. 243–264 (Chapter 8).
Eyckmans, J., Tulkens, H., 2003. Simulating coalitionally stable burden sharing agreements for the climate change problem. Resource and Energy Economics 25, 299–327.
Germain, M., Toint, Ph., Tulkens, H., 1998a. Financial transfers to ensure cooperative international optimality in stock pollutant abatement. In: Faucheux, S., Gowdy, J., Nicolaï, I. (Eds.), Sustainability and Firms: Technological Change and the Changing Regulatory Environment. Cheltenham, Edward Elgar (Chapter 11).
Germain, M., Tulkens, H., de Zeeuw, A., 1998b. Stabilité stratégique en matière de pollution internationale avec effet de stock: Le cas linéaire. Revue Economique 49 (6), 1435–1454.
Germain, M., Toint, P., Tulkens, H., de Zeeuw, A., 2003. Transfers to sustain dynamic core-theoretic cooperation in international stock pollutant control. Journal of Economic Dynamics and Control 28, 79–99.
Hoel, M., 1992. Emission taxes in a dynamic international game of CO$ _{2}$ emissions. In: Pethig, R. (Ed.), Conflicts and Cooperation in Managing Environmental Resources. In: Microeconomic Studies, Springer Verlag, Berlin.
Jorgensen, S., Martin-Herran, G., Zaccour, G., 2003. Agreeability and time consistency in linear-state differential games. Journal of Optimization Theory and Applications 119 (1), 49–63.
Kaitala, V., Mäler, K.G., Tulkens, H., 1995. The acid rain game as a resource allocation process, with application to negotiations between Finland, Russia and Estonia. The Scandinavian Journal of Economics 97 (2), 325–343. Reprinted in Carlo Carraro, Ed., Governing the Global Environment, The Globalization of the World Economy, An Elgar Reference Collection, Cheltenham 2003.
Kaitala, V., Pohjola, M., Tahvonen, O., 1992. Transboundary air pollution and soil acidification: A dynamic analysis of an acid rain game between Finland and the USSR. Environmental and Resource Economics 2, 161–181.
Mäler, K.-G., 1989. The acid rain game. In: Folmer, H., van Ierland, E. (Eds.), Valuation Methods and Policy Making in Environmental Economics. Elsevier, Amsterdam.
Petrosjan, L., Zaccour, G., 1995. A multistage supergame of downstream pollution, G-95-14, GERAD, Ecole des Hautes Etudes Commerciales, Université de Montréal.
van der Ploeg, F., de Zeeuw, A., 1992. International aspects of pollution control. Environmental and Resource Economics 2, 117–139.
Rubio, S.J., Ulph, A., 2007. An infinite-horizon model of dynamic membership of international environmental agreements. Journal of Environmental Economics and Management 54 (3), 296–310.
Tahvonen, O., 1994. Carbon dioxyde abatement as a differential game. European Journal of Political Economy 10 (4), 685–705.
Tulkens, H., 1979. An economic model of international negotiations relating to transfrontier pollution. In: Krippendorff, K. (Ed.), Communication and Control in Society. Gordon and Breach, New York, pp. 199–212. Reprinted as chapter 5 (pp. 107–122) in P. Chander, J. Drèze, C.K. Lovell and J. Mintz, eds., Public goods, environmental externalities and fixed competition, Springer, 2006.

Environmental Economics & Management Memoranda

130. Marc FLEURBAEY, Thibault GAJDOS and Stéphane ZUBER. Social rationality, separability, and equity under uncertainty. (also CORE discussion paper 2010/37).

129. Stéphane ZUBER. Justifying social discounting: the rank-discounted utilitarian approach. (also CORE discussion paper 2010/36).

128. Antoine BOMMIER and Stéphane ZUBER. The Pareto principle of optimal inequality. (also CORE discussion paper 2009/9).

127. Thomas BAUDIN. A role for cultural transmission in fertility transitions. *Macroeconomic Dynamics*, 14, 2010, 454-481.

126. Thomas BAUDIN. The optimal trade-off between quality and quantity with uncertain child survival. October 2010.

125. Thomas BAUDIN. Family Policies: What does the standard endogenous fertility model tell us? September 2010.

124. Philippe VAN PARIJS. Un "Sustainable New Deal" pour la Belgique. Forum annuel du Conseil fédéral pour le développement durable, The Square, 16 novembre 2009.

123. Thierry BRECHET, François GERARD, Henry TULKENS. Efficiency *vs*. stability of climate coalitions: a conceptual and computational appraisal. *The Energy Journal* 32(1), 49-76, 2011.

122. Maria Eugenia SANIN, Skerdilajda ZANAJ. A note on clean technology adoption and its influence on tradable emission permits prices. *Environmental and Resource Economics*, in press, 2010.

121. Thierry BRECHET, Julien THENIE, Thibaut ZEIMES, Stéphane ZUBER. The benefits of cooperation under uncertainty: the case of climate change (also CORE discussion paper 2010/62).

120. Thierry BRECHET, Yuri YATSENKO, Natali HRITONENKO. Adaptation and mitigation in long-term climate policies (also CORE discussion paper).

119. Marc GERMAIN, Alphonse MAGNUS, Henry TULKENS. Dynamic core-theoretic cooperation in a two-dimensional international environmental model. *Mathematical Social Sciences*, 59(2), 208-226, 2010.

118. Thierry BRECHET, Pierre M. PICARD. The price of silence: markets for noise licenses and airports. *International Economic Review*, 51(4), 1097-1125, 2010.

117. Thierry BRECHET, Pierre-André JOUVET, Gilles ROTILLON. Tradable pollution permits in dynamic general equilibrium: can optimality and acceptability be reconciled? (also CORE discussion paper 2010/56).

116. Thierry BRECHET, Stéphane LAMBRECHT. Renewable resource and capital with a joy-of-giving resource bequest motive. *Resource and Energy Economics*, in press, 2010.

115. Thierry BRECHET, Alain AYONG LE KAMA. Public environmental policies: some insights from economic theory. *International Economics* 120(4), 5-10, 2009.

114. Thierry BRECHET, Johan EYCKMANS, François GERARD, Philippe MARBAIX, Henry TULKENS, Jean-Pascal van YPERSELE. The impact of the unilateral EU commitment on the stability of international climate agreements. *Climate Policy*, 10, 148-166, 2010.

113. Thierry BRECHET, Sylvette LY. Technological greening, eco-efficiency and no-regret strategy. March 2010.

112. Thierry BRECHET, Fabien PRIEUR. Can education be good for both growth and the environment? (also CORE discussion paper 2009/19).

111. Carlotta BALESTRA, Thierry BRECHET, Stéphane LAMBRECHT. Property rights and biological spillovers: when Hardin meats Meade. February 2010 (also CORE DP 2010/ ?).

110. Thierry BRECHET, Tsvetomir TSACHEV, Vladimir VELIOV. Markets for emission permits with free endowment : a vintage capital analysis. February 2010 (also CORE DP 2010/ ?).

109. Thierry BRECHET, Fabien PRIEUR. Public investment in environmental infrastructures, growth, and the environment. January 2010 (also CORE DP 2010/ ?).

108. Kirill BORISSOV, Thierry BRECHET, Stéphane LAMBRECHT. Median voter environmental maintenance. February 2010 (also CORE DP 2010/ ?).

107. Thierry BRECHET, Carmen CAMACHO, Vladimir VELIOV. Model predictive control, the economy, and the issue of global warming. January 2010 (also CORE DP 2010/ ?).

106. Thierry BRECHET, Tsvetomir TSACHEV and Vladimir M. VELIOV. Prices versus quantities in a vintage capital model. In : *Dynamic Systems, Economic Growth, and the Environment*, Jesus Crespo Cuaresma, Tapio Palokangas, Alexander Tarasyev (eds), Dynamic Modeling and Econometrics in Economics and Finance 12, 141-159, 2010.

105. Thierry BRECHET, Pierre-André JOUVET. Why environmental management may yield no-regret pollution abatement options. *Ecological Economics*, 68, 1770-1777, 2009.

104. Thierry BRECHET et Henry TULKENS. Mieux répartir les coûts de la politique climatique. *La vie des idées.fr*, 2009.

103. Thierry BRECHET. Croissance économique, environnement et bien-être. In : Alain Ayong Le Kama, Pour une croissance verte … et sociale, *La lettre de l'AFSE*, 74:9-13, 2009.

102. Henry TULKENS. Stabilité de l'accord et règles d'allocation initiale des droits d'émission. Commentaire sur le Rapport de Jean Tirole "Politique climatique : une nouvelle architecture internationale", 9 octobre 2009.

101. Giorgia OGGIONI, Yves SMEERS. Evaluatinq the impact of average cost based contracts on the industrial sector in the European emission trading scheme. *CEJOR* 17:181-217, 2009.

100. Raouf BOUCEKKINE, Marc GERMAIN. The burden sharing of polllution abattement costs in multi-regional open economics. *The B.E. Journal of Macroeconomics*, 9 (1 Topics), 2009.

99. Rabah AMIR, Marc GERMAIN, Vincent VAN STEENBERGHE. On the impact of innovation on the marginal abatement cost curve. *Journal of Public Economic Theory*, 10(6):985-1010, 2008.

98. Maria Eugenia SANIN, Skerdilajda ZANAJ. Clean technology adoption and its influence on tradeable emission permit prices. April 2009 (also CORE DP 2009/29).

97. Jerzy A. FILAR, Jacek B. KRAWCZYK, Manju AGRAWAL. On production and abatement time scales in sustainable development. Can we loose the *sustainability screw* ? April 2009 (also CORE DP 2009/28).

96. Giorgia OGGIONI, Yves SMEERS. Evaluating the impact of average cost based contracts on the industrial sector in the European emission trading scheme. *CEJOR* (2009) 17: 181-217.

95. Marc GERMAIN, Henry TULKENS, Alphonse MAGNUS. Dynamic core-theoretic cooperation in a two-dimensional international environmental model, April 2009 (also CORE DP 2009/21).

94. Henry TULKENS, Vincent VAN STEENBERGHE. "Mitigation, Adaptation, Suffering" : In search of the right mix in the face of climate change, June 2009.

93. Luisito BERTINELLI, Eric STROBL. The environmental Kuznets curve semi-parametrically revisited. *Economics Letters,* 88 (2005) 350-357.

92. Maria Eugenia SANIN, Francesco VIOLANTE. Understanding volatility dynamics in the EU-ETS market: lessons from the future, March 2009 (also CORE DP 2009/24).

91. Thierry BRECHET, Henry TULKENS. Beyond BAT : Selecting optimal combinations of available techniques, with an example from the limestone industry. *Journal of Environmental Management*, 90:1790-1801, 2009.

90. Giorgia OGGIONI, Yves SMEERS. Equilibrium models for the carbon leakage problem. December 2008 (also CORE DP 2008/76).

89. Giorgia OGGIONI, Yves SMEERS. Average power contracts can mitigate carbon leakage. December 2008 (also CORE DP 2008/62).

88. Thierry BRECHET, Johan EYCKMANS, François GERARD, Philippe MARBAIX, Henry TULKENS, Jean-Pascal van YPERSELE. The impact of the unilateral EU commitment on the stability of international climate agreements. (also CORE DP 2008/61).

87. Raouf BOUCEKKINE, Jacek B. KRAWCZYK, Thomas VALLEE. Towards an understanding of tradeoffs between regional wealth, tightness of a common environmental constraint and the sharing rules. (also CORE DP 2008/55).

86. Thierry BRECHET, Tsvetomir TSACHEV, Vladimir VELIOV. Prices versus quantities in a vintage capital model. March 2009 (also CORE DP 2009/15).

85. David DE LA CROIX, Davide DOTTORI. Easter Island's collapse : a tale of a population race. *Journal of Economic Growth*, 13:27-55, 2008.

84. Thierry BRECHET, Stéphane LAMBRECHT, Fabien PRIEUR. Intertemporal transfers of emission quotas in climate policies. *Economic Modelling*, 26(1):126-143, 2009.

83. Thierry BRECHET, Stéphane LAMBRECHT. Family altruism with renewable resource and population growth. *Mathematical Population Studies*, 16:60-78, 2009.

82. Thierry BRECHET, Alexis GERARD, Giordano MION. Une évaluation objective des nuisances subjectives de l'aéroport de Bruxelles-National. *Regards Economiques*, 66, Février 2009.

81. Thierry BRECHET, Johan EYCKMANS. Coalition theory and integrated assessment modeling : Lessons for climate governance. In E. Brousseau, P.A. Jouvet and T. Tom Dedeurwaerder (eds). Governing Global Environmental Commons: Institutions, Markets, Social Preferences and Political Games, Oxford University Press, 2009.

80. Parkash CHANDER and Henry TULKENS. Cooperation, stability, and self-enforcement in international environmental agreements : A conceptual discussion. In R. Guesnerie and H. Tulkens (eds). *The Design of Climate Policy*, CESifo Seminar Series, The MIT Press, 2008.

79. Mirabelle MUULS. The effect of investment on bargaining positions. Over-investment in the case of international agreements on climate change. September 2008

78. Pierre-André JOUVET, Philippe MICHEL, Pierre PESTIEAU. Public and private environmental spending : a political economy approach. *Environmental Economics and Policy Studies*, 9(3):177-191, 2008.

77. Fabien PRIEUR. The environmental Kuznets curve in a world of irreversibility. *Economic Theory*, 40(1) : 57-90, 2009.

76. Raouf BOUCEKKINE, Natali HRITONENKO and Yuri YATSENKO. Optimal firm behavior under environmental constraints. April 2008. (also CORE DP 2008/24).

75. Giorgia OGGIONI and Yves SMEERS. Evaluating the impact of average cost based contracts on the industrial sector in the European emission trading scheme. January 2008 (also CORE DP 2008/1).

74. Thierry BRECHET and Pierre-André JOUVET. Environmental innovation and the cost of pollution abatement revisited. *Ecological Economics*, 65:262-265, 2008.

73. Ingmar SCHUMACHER and Benteng ZOU. Pollution perception : A challenge for intergenerational equity. *Journal of Environmental Economics and Management*, 55, 296-309, 2008.

72. Thierry BRECHET et Patrick VAN BRUSSELEN. Le pic pétrolier: un regard d'économiste. *Reflets et Perspectives de la vie économique*, Tome XLVI, n° 4, 63-81, 2007.

71. Thierry BRECHET. L'énergie : mutations passées et mutations en cours. *Reflets et Perspectives de la vie économique*, Tome XLVI, n° 4, 5-11, 2007.

70. Marc GERMAIN, Alphonse MAGNUS and Vincent VAN STEENBERGHE. How to design and use the clean development mechanism under the Kyoto Protocol? A developing country perspective. *Environmental & Resource Economics*, 38(1):13-30, 2007.

69. Thierry BRECHET en Pierre PICARD. Economische instrumenten voor de regulering van de geluidshinder in de omgeving van luchthavens? *Brussels Studies*, nummer 12, 3 december 2007.

68. Thierry BRECHET et Pierre PICARD. Des instruments économiques pour la régulation des nuisances sonores autour des aéroports? *Brussels Studies*, numéro 12, 3 décembre 2007, www.brusselsstudies.be.

67. Thierry BRECHET and Pierre PICARD. Can economic instruments regulate noise pollution in locations near airports? *Brussels Studies*, issue 12, 2007 December the 3rd , www.brusselsstudies.be.

66. Pierre-André JOUVET, Pierre PESTIEAU and Gregory PONTHIERE. Longevity and Environmental quality in an OLG model. September 2007 (also available as CORE DP 2007/69).

65. Raouf BOUCEKKINE and Marc GERMAIN. Impacts of emission eduction policies in a multi-regional multi-sectoral small open economy with endogenous growth. February 2007 (also available CORE DP 2007/11).

64. Parkash CHANDER and Subhashini MUTHUKRISHNAN. Green consumerism and collective action. June 2007 (also available as CORE DP 2007/58).

63. Jakub GROWIEC and Ingmar SCHUMACHER. Technological opportunity, long-run growth and convergence. July 2007 (also available as CORE DP 2007/57).

62. Maria Eugenia SANIN and Skerdilajda ZANAJ. Environmental innovation under Cournot competition. June 2007. (also available as CORE DP 2007/50)

61. Thierry BRECHET and Stéphane LAMBRECHT. Family altruism with a renewable resource and population growth. October 2006 (also available as CORE DP 2006/35).

60. Thierry BRECHET, François GERARD and Henry TULKENS. Climate Coalitions: a theoretical and computational appraisal. February 2007 (also available as CORE DP 2007/3).

59. Thierry BRECHET. L'environnement dans tous ses états. *Regards Economiques*, n° 50, 26-32, Avril 2007.

58. Thierry BRECHET and Susana PERALTA. The race for polluting permitsThierry. March 2007 (also available as CORE DP 2007/27).

57. Giorgia OGGIONI, Ina RUMIANTSEVA and Yves SMEERS. Introduction of CO_2 emission certificates in a simplified model of the Benelux electricity network with small and industrial consumers. Reprint from *Proceedings of the International Conference on Clean Electrical Power*, Capri, Italy, May 21-23, 2007.

56. Agustin PEREZ-BARAHONA. The problem of non-renewable energy resource in the production of physical capital. January 2007 (also available as CORE DP 2007/8).

55. Thierry BRECHET, Benoît LUSSIS. The contribution of the clean development mechanism to national climate policies. *Journal of Policy Modelling*, 28(9), 981-994, December 2006.

54. Ingmar SCHUMACHER. Endogenous discounting via wealth, twin-peaks and the role of technology. November 2006 (also available as CORE DP 2006/104).

53. Ingmar SCHUMACHER. On optimality, endogenous discounting and wealth accumulation. October 2006 (also available as CORE DP 2006/103).

52. Jakub GROWIEC, Ingmar SCHUMACHER. On technical change in the elasticities of resource inputs. November 2006. (also available as CORE DP 2006/63).

51. Maria Eugenia SANIN. Market Design in Wholesale Electricity Markets. October 2006 (also available as CORE DP 2006/100).

50. Luisito BERTINELLI, Eric STROBL and Benteng ZOU. Polluting technologies and sustainable economic development. June 2006 (also available as CORE DP 2006/52).

49. Marc GERMAIN, Alphonse MAGNUS. Prices versus quantities: Stock pollution control with repeated choice of the instrument. October 2005. *Journal of Computational and Applied Mathematics*, 197 (2006) 437-445.

48. Agustin PEREZ-BARAHONA. Capital accumulation and exhaustible energy resources: a special functions case. September 2006 (also available as CORE DP 2007/9).

47. Philippe TULKENS, Henry TULKENS. The White House and the Kyoto Protocol: Double standards on uncertainties and their consequences. May 2006 (also TERI School of Advanced Studies WP Series #1).

46. Thierry BRECHET, Pierre-André JOUVET. Environmental innovation and the cost of pollution abatement. January 2006 (also available as CORE DP 2006/40).

45. Fabien PRIEUR. The implication of irreversible pollution on the relation between growth and the environment: The degenerate Kuznets curve. February 2006.

44. Thierry BRECHET, Marc GERMAIN, Philippe MONTFORT. Allocation des efforts de dépollution dans des économies avec spécialisation internationale. *Revue Economique*, 57(2), Mars 2006.

43. Ingmar SCHUMACHER and Benteng ZOU. Habit in Pollution, A Challenge for Intergenerational Equity. March 2006 (also available as CORE DP 2006/6).

42. Jean-Charles HOURCADE, P.R. SHUKLA and Sandrine MATHY. Cutting the Climate-Development Gordian Knot – Economic options in a politically constrained world. September 2005.

41. Urs LUTERBACHER. Climate Change, the Kyoto Protocol, and Transatlantic Relations. November 2005.

40. Parkash CHANDER and Henry TULKENS. Cooperation, Stability and Self-Enforcement in International Environmental Agreements: A Conceptual Discussion. July 2005.

39. Paul-Marie BOULANGER et Thierry BRECHET. Le Mécanisme pour un Développement Propre tiendra-t-il ses promesses ? *Reflets et Perspectives de la Vie Economique*, Tome XLIV – 2005 – N° 3, 5-27.

38. Paul-Marie BOULANGER and Thierry BRECHET. Models for policy-making in sustainable development: The state of the art and perspectives for research. *Ecological Economics*, 55, 337-350, 2005.

37. Johan EYCKMANS an Henry TULKENS. Optimal and Stable International Climate Agreements. October 2005. Reprint from "*Economic Aspects of Climate Change Policy : A European and Belgian Perspective*", a joint product of CES-K.U.Leuven and CORE-UCL, edited by Bert Willems, Johan Eyckmans and Stef Proost, published by ACCO, 3000 Leuven (Belgium)

36. Thierry BRECHET and Benoît LUSSIS. The Clean Development Mechanism in Belgian Climate Policy. October 2005. Reprint from "*Economic Aspects of Climate Change Policy : A European and Belgian Perspective*", a joint product of CES-K.U.Leuven and CORE-UCL, edited by Bert Willems, Johan Eyckmans and Stef Proost, published by ACCO, 3000 Leuven (Belgium)

35. Vincent VAN STEENBERGHE. The impact of banking on permits prices and compliance costs. October 2005. Reprint from "*Economic Aspects of Climate Change Policy : A European and Belgian Perspective*", a joint product of CES-K.U.Leuven and CORE-UCL, edited by Bert Willems, Johan Eyckmans and Stef Proost, published by ACCO, 3000 Leuven (Belgium)

34. Johan EYCKMANS, Denise VAN REGEMORTER and Vincent VAN STEENBERGHE. Kyoto-permit prices and compliance costs: an analysis with MacGEM. October 2005. Reprint from "*Economic Aspects of Climate Change Policy : A European and Belgian Perspective*", a joint product of CES-K.U.Leuven and CORE-UCL, edited by Bert Willems, Johan Eyckmans and Stef Proost, published by ACCO, 3000 Leuven (Belgium)

33. Johan EYCKMANS, Bert WILLEMS and Jean-Pascal VAN YPERSELE. Climate Change: Challenges for the World. October 2005. Reprint from "*Economic Aspects of Climate Change Policy : A European and Belgian Perspective*", a joint product of CES-K.U.Leuven and CORE-UCL, edited by Bert Willems, Johan Eyckmans and Stef Proost, published by ACCO, 3000 Leuven (Belgium)

32. Marc GERMAIN, Stef PROOST and Bert SAVEYN. The Belgian Burden Sharing. October 2005. Reprint from "*Economic Aspects of Climate Change Policy : A European and Belgian Perspective*", a joint product of CES-K.U.Leuven and CORE-UCL, edited by Bert Willems, Johan Eyckmans and Stef Proost, published by ACCO, 3000 Leuven (Belgium)

31. Ingmar SCHUMACHER. Reviewing Social Discounting within Intergenerational Moral Intuition. June 2005.

30. Stéphane LAMBRECHT. The effects of a demographic shock in an OLG economy with pay-as-you-go pensions and property rights on the environment: the case of selfish households. January 2005.

29. Stéphane LAMBRECHT. Maintaining environmental quality for overlapping generations: Some Reflections on the US Sky Trust Initiative. May 2005.

28. Thierry BRECHET, Benoît LUSSIS. The contribution of the Clean Development Mechanism to national climate policies. April 2005.

27. Thierry BRECHET, Stéphane LAMBRECHT, Fabien PRIEUR. Intergenerational transfers of pollution rights and growth. May 2005 (also availabe as CORE DP 2005/42).

26. Maryse LABRIET, Richard LOULOU. From non-cooperative CO_2 abatement strategies to the optimal world cooperation: Results from the integrated MARKAL model. April 2005.

25. Marc GERMAIN, Vincent VAN STEENBERGHE, Alphonse MAGNUS. Optimal Policy with Tradable and Bankable Pollution Permits : Taking the Market Microstructure into Account.*Journal of Public Economy Theory*, 6(5), 2004, 737-757.

24. Marc GERMAIN, Stefano LOVO, Vincent VAN STEENBEGHE. De l'impact de la microstructure d'un marché de permis de polluer sur la politique environnementale. *Annales d'Economie et de Statistique*, n° 74 – 2004, 177-208.

23. Marc GERMAIN, Alphonse MAGNUS, Vincent VAN STEENBERGHE. Should developing countries participate in the Clean Development Mechanism under the Kyoto Protocol ? The low-hanging fruits and baseline issues. December 2004.

22. Thierry BRECHET et Paul-Marie BOULANGER. Le Mécanisme pour un Développement Propre, ou comment faire d'une pierre deux coups. *Regards Economiques*, Ires n° 27, janvier 2005.

21. Sergio CURRARINI & Henry TULKENS. Stable international agreements on transfrontier pollution with ratification constraints. In C. Carraro and V. Fragnelli (eds.), *Game Practice and the Environment*. Cheltenham, Edward Elgar Publishing, 2004, 9-36. (also available as CORE Reprint 1715).

20. Agustin PEREZ-BARAHONA & Benteng ZOU. A comparative study of energy saving technical progress in a vintage capital model. December 2004.

19. Agustin PEREZ-BARAHONA & Benteng ZOU. Energy saving technological progress in a vintage capital model. December 2004.

18. Matthieu GLACHANT. Voluntary agreements under endogenous legislative threats and imperfect enforcement. November 2004.

17. Thierry BRECHET, Stéphane LAMBRECHT. Puzzling over sustainability: an equilibrium analysis. November 2004.

16. Vincent VAN STEENBERGHE. Core-stable and equitable allocations of greenhouse gas emission permits. October 2004. (also available as CORE DP 2004/75).

15. Pierre-André JOUVET Philippe MICHEL, Pierre PESTIEAU. Public and private environmental spending. A political economy approach. September 2004. (also available as CORE DP 2004/68).

14. Thierry BRECHET, Marc GERMAIN, Vincent VAN STEENBERGHE. The clean development mechanism under the Kyoto protocol and the 'low-hanging fruits' issue. July 2004. (also available as CORE DP 2004/81).

13. Thierry BRECHET, Philippe MICHEL. Environmental performance and equilibrium. July 2004. (also available as CORE DP 2004/72).

12. Luisito BERTINELLI, Eric STROBL. The Environmental Kuznets Curve semi-parametrically revisited. July 2004. (also available as CORE DP 2004/51).

11. Axel GOSSERIES, Vincent VAN STEENBERGHE. Pourquoi des marchés de permis de polluer ? Les enjeux économiques et éthiques de Kyoto. April 2004. (also available as IRES discussion paper n° 2004-21).

10. Vincent VAN STEENBERGHE. CO_2 Abatement costs and permits price : Exploring the impact of banking and the role of future commitments. December 2003. (also available as CORE DP 2003/98).

9. Katheline SCHUBERT. Eléments sur l'actualisation et l'environnement. March 2004.

8. Marc GERMAIN. Modélisations de marchés de permis de pollution. July 2003.

7. Marc GERMAIN. Le Mécanisme de Développement Propre : Impacts du principe d'additionalité et du choix de la baseline. January 2003.

6. Thierry BRECHET et Marc GERMAIN. Les affres de la modélisation. May 2002.

5. Marc GERMAIN and Vincent VAN STEENBERGHE. Constraining equitable allocations of tradable CO_2 emission quotas by acceptability, *Environmental and Resource Economics*, (26) 3, 2003.

4. Marc GERMAIN, Philippe TOINT, Henry TULKENS and Aart DE ZEEUW. Transfers to sustain dynamic core-theoretic cooperation in international stock pollutant control, *Journal of Economic Dynamics & Control*, (28) 1, 2003.

3. Thierry BRECHET, Marc GERMAIN et Philippe MONTFORT. Spécialisation internationale et partage de la charge en matière de réduction de la pollution. (also available as IRES discussion paper n°2003-19).

2. Olivier GODARD. Le risque climatique planétaire et la question de l'équité internationale dans l'attribution de quotas d'émission échangeable. May 2003.

1. Thierry BRECHET. Entreprise et environnement : des défis complémentaires ? March 2002. Revue Louvain.

Environmental Economics & Management Memorandum

Chair Lhoist Berghmans in Environmental Economics and Management
Center for Operations Research & Econometrics (CORE)
Université catholique de Louvain (UCL)
Voie du Roman Pays 34
B-1348 Louvain-la-Neuve, Belgium

Hard copies are available upon request : env@core.ucl.ac.be
Papers are available in pdf format on line : http://www.uclouvain.be/en-21264.html