Fondazione Eni Enrico Mattei

NOTA DI LAVORO

108.2013

The Global Emission Game: On the Impact of Strategic Interactions Between Countries on the Existence and Properties of Nash Equilibria

By **Mélanie Heugues**, Fondazione Eni Enrico Mattei, Italy

Climate Change and Sustainable Development
Series Editor: Carlo Carraro

The Global Emission Game: On the Impact of Strategic Interactions Between Countries on the Existence and the Properties of Nash Equilibria

By Mélanie Heugues, Fondazione Eni Enrico Mattei, Italy

Summary

In a context of *laissez-faire*, the propositions established in this paper shed light on the evolution of the problem of greenhouse gas (GHG) accumulation in the atmosphere for each type of strategic behaviour resulting from countries' interconnection on global markets. In a framework of strong economic interdependencies, they show the potential consequences of the free trade arrangements on the environment and question the idea that free trade liberalisation should necessarily lead to an increase in countries' welfare. This paper provides an exhaustive typology of countries' strategic behaviours and a strong static comparative analysis with regard to the exogenous parameters of the model. Whereas some assumptions tend to be less relevant from an environmental point of view; others that are very relevant have not yet been considered in the literature. Using lattice theoretic notions, this paper generalizes the existing results of the literature and determines new equilibria not yet exploited. It thus extends the current framework of the traditional public economic theory dealing with public goods.

Keywords: Non-Cooperative Game Theory, Climate Change, Global Emission Game, Nash Equilibria, Strategic Substitutes and Complements

JEL Classification: C72, H41, Q54

This work is part of the Marie Curie project INTCOP21: "Policy linkages and international cooperation on climate change: Who cares about the economic burden of the environment?". The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 2010-273297.

Address for correspondence:

Mélanie Heugues
Fondazione Eni Enrico Mattei
Corso Magenta 63
20123 Milano
Italy
Phone: +33 632 063 776
E-mail: melanie.heugues@feem.it

The global emission game:

On the impact of strategic interactions between countries on the existence and the properties of Nash equilibria

Mélanie Heugues

Fondazione Eni Enrico Mattei, Corso Magenta 63, 20123 Milano, Italy

e-mail: melanie.heugues@feem.it

Phone: +33 632 063 776

Draft October 2013

Abstract

In a context of *laissez-faire*, the propositions established in this paper shed light on the evolution of the problem of greenhouse gas (GHG) accumulation in the atmosphere for each type of strategic behaviour resulting from countries' interconnection on global markets. In a framework of strong economic interdependencies, they show the potential consequences of the free trade arrangements on the environment and question the idea that free trade liberalisation should necessarily lead to an increase in countries' welfare. This paper provides an exhaustive typology of countries' strategic behaviours and a strong static comparative analysis with regard to the exogenous parameters of the model. Whereas some assumptions tend to be less relevant from an environmental point of view; others very relevant have not yet been considered in the literature. Using lattice theoretic notions, this paper generalizes the existing results of the literature and determines new equilibria not yet exploited. It thus extends the current framework of the traditional public economic theory dealing with public goods.

Key words: Non-cooperative game theory; climate change; global emission game; Nash equlibria; strategic substitutes and complements.

JEL Classification: C72; H41; Q54.

* This work is part of the Marie Curie project INTCOP21: "Policy linkages and international cooperation on climate change: Who cares about the economic burden of the environment?". The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 2010-273297.

1. Introduction

The distinctive characteristics of the problem of climate change turn it into a big challenge. First of all, the environment – or the atmosphere, is a global public good that countries are free to provide or to enjoy. It means that there is not a unique well identified and settled agent responsible for greenhouse gas (GHG) emissions; emissions are rather the indirect consequence of the performance of a large group of economies. Secondly, States are sovereign and no supranational authority exists to implement a globally optimal environmental policy: each country has thus to decide voluntarily to reduce its GHG emissions given a strong incentive to free ride. Finally, even if countries agree on the existence of the problem and its urgency, national emissions are a strategic variable since they are linked to national economic activities, and thus to economic growth and development.

Our paper relies on the literature studying international cooperation on climate change and using non cooperative game theory. With regard to this literature, the efforts have been essentially concentrated on the question of countries' cooperation, rarely questioning the nature of the interactions between countries (Carraro and Siniscalco, 1993). Nonetheless this question is fundamental because it determines the eventual consequences of the unilateral implementation of environmental policies.[1] In this literature, the almost universal argument put forward has been that if a country or a group of countries undertakes to reduce its emissions, the outsiders will have a positive incentive to increase their own emissions, partially or totally cancelling the initial effort undertaken (Barrett, 1994, Carraro and Siniscalco, 1993, Diamantoudi and Sartzetakis, 2006). In this case, strategies are supposed to be substitutable. Nonetheless, a more recent literature in trade theory tends to show that reinforcement effects exist between countries' strategies, i.e. that the latter could be complementary as well. This phenomenon would be linked to trade liberalization and countries' increasing inter-connexion on global markets, i.e. that trade liberalization has fundamentally modified countries' interactions over emission levels (Copeland and Taylor, 2005).[2]

In this paper we stay at a prior step reconsidering the substrate of a potential international agreement; i.e. reconsidering the nature of the interactions between countries. In this respect, there are two alternatives: countries' strategies are either substitutable or complementary. [3,4] The propositions are established from the game in emissions, known in the literature as "*the global emission game*".[5] It depicts a framework of strong interactions between countries, where payoffs vary according to countries' own strategy and the strategy adopted by the others. In a purely non cooperative setting, each country determines its individual strategy maximizing its own payoff given the strategy adopted by the others.

---

[1] See Hoel (1991) analysing the consequences of one country reducing its emissions unilaterally when other countries' policy is dictated by their self-interest and Barrett (2003) developing a theory that explains both the successes and the failures of treaties dealing with environmental problems such as climate change, acid rains, depletion of the ozone layer, and so on.

[2] The paper defends the idea that the traditional arguments supporting the nature of the interactions between countries are incomplete or only valid in a closed economy setting.

[3] The first alternative (the most frequent in the literature) is generally justified by the existence of carbon leakage exacerbating the free-riding phenomenon. The second can be justified through international spillovers (technological, political and social) because of an increasing phenomenon of competitive interactions between governments (Pitlik, 2007).

[4] From a theoretical point of view, Copeland and Taylor (2005) put into light the conditions of emergence of one kind of complementarity between countries' strategies using a computable general equilibrium model.

[5] An alternative game is the one in abatement (Barrett, 1994).

The aim of this paper is to show that the assumption on the nature of the interactions between countries has fundamental impacts on the conditions of existence and the static comparative properties of the Nash equilibria of the game. We thus provide an exhaustive analysis of all the possible equilibria and we study their respective static comparative properties. In particular the consequences in terms of pollution are not the same when considering 2 or 200 countries. The scale of the problem will thus influence individual and global emission levels as well as countries' payoff. Existing studies, such as the one by Finus (2001), provide results that overlap with the ones in this paper. Nonetheless the latter rely on methods based on the implicit function theorem and signing derivatives.[6] In addition the case with multiple equilibria is systematically dismissed. The originality of our work relies on the use of lattice methods. This methodology is particularly suited to establish strong static comparative results and relies on minimal assumptions relative to the traditional approach (Milgrom, Roberts, 1994; Amir, Lambson, 2000).[7] We are able to compare equilibria eschewing restrictive assumptions such as quasi-concave payoff functions, existence or uniqueness of equilibrium. Focusing on the global structure of the equilibrium set, we compare the extreme equilibria showing how the behaviours predicted change with changing the exogenous parameters of the model.

Formally, the analysis relies on the sign of the cross partial derivative of the payoff function relative to the strategic variables of the model.[8] Because of the definition of the game, this sign is directly connected with the sense of evolution of the gross marginal benefit countries get from their own emissions. When gross marginal benefits are decreasing, countries' strategies are globally complementary and the game always has at least one pure-strategy Nash equilibrium. The traditional framework of the literature belongs to this alternative. We also show that the problem can become particularly serious when reinforcement effects exist between economic activity levels, i.e. when strategies are such that each country chooses its emission level as high as the one of the others is high. In this perspective, a first step for international cooperation could be to coordinate on the lowest individual emissions levels leading to the highest payoff levels. On the contrary, when gross marginal benefits are increasing, countries' strategies are globally substitutable or strongly substitutable. In this case we have to define stronger conditions in order to ensure the equilibrium existence in the game. Moreover, even if it's commonly admitted that the problem gets worse with the number of interacting countries, we show that this assertion is not always true, _which is questionable on an environmental ground. Finally, under both alternatives, the perception countries have of the environmental damages relative to the benefit of their emissions also plays a role in the determination of individual emission levels.

The remainder of the paper is organised as follows. Section 2 describes the global emission game and provides fundamental assumptions on countries' payoff functions and strategy sets. Section 3 defines the conditions of existence of equilibrium in a purely non cooperative framework whereas section 4 provides several results of static comparative relative to the exogenous parameter of the model. Section 5 concludes. Appendix A contains the definitions and theorems needed for our approach such that the paper is self-contained and Appendix B provides the proofs of the propositions.

[6] Based on the implicit function theorem, static comparative conclusions are only valid locally.

[7] For example, analyses based on the implicit function theorem are not able to provide conclusions in the presence of non-convexities or multiple equilibria.

[8] The assumption of derivability is only made for convenience and does not constitute a limit for the majority of the results presented.

2. The global emission game: fundamental functions and assumptions

In this section we briefly present the game as it appears traditionally in the literature and then we provide an alternative version for the sake of our purpose. We consider n identical countries with $N = \{1, ..., n\}$. Linked to economic activities, each of them emits GHGs, $x \geq 0$, that mix uniformly in the atmosphere. In its most general form, the payoff function of country i, f_i, is expressed as the difference between the benefits of its own emissions, $B(x_i)$, and the damages linked to global emissions, $D(\sum_{i \in N} x_i)$. The strategic choice made by a country is thus its emission level.[9] Given symmetry, we note in the following x, y and z respectively the emission level of the country under consideration, the aggregate emission level of the $(n-1)$ other countries, and the global emission level, i.e. $z = x + y$. A country's payoff function is thus of the form:

$$f(x, y) = B(x) - D(x + y). \qquad (1)$$

The only assumptions we do for the while on the benefit and the damage functions are the following: $B'(x) \geq 0$ and $D'(x) \geq 0$; i.e. countries' benefits are an increasing function of their own emissions whereas damages are an increasing function of global emissions. It's through this latter assumption that the problem at stake gets its global character.

In what follows $f(\cdot)$ is defined on the strategy set $X = [0, K]$ which is a compact interval of the real positive. We define K as the maximal capacity of pollution of a country or also as its maximum production capacity. Decisions are supposed to be taken simultaneously: each country determines its emission level maximizing its payoff function and given the anticipation he has on the strategies adopted by the others. From equation (1), we define $X(y)$ as the *individual best-response correspondence* of the country under consideration. $X(y)$ is the set of solutions of the problem of maximization of one country. At an equilibrium point, the conjectures of all countries coincide: given the strategy of the others, none has an incentive to change its strategy unilaterally. Note also that the assumption of symmetric countries does not alter our conclusions, the central idea being the existence of strategic interdependencies between countries: the damage a country bears depends on its own strategy and on the aggregated strategy of the $(n-1)$ other countries, but the distribution of emission levels among countries has no interest.

To extend the existing framework of the literature and to undertake a typology of countries' strategies, we need to consider a monotone transformation of the game. This procedure is borrowed from Amir and Lambson (2000) and relies on the aggregative nature of the problem.[10] In the alternative game, the country under consideration chooses $z = x + y$ given the aggregated strategy of the $(n-1)$ other countries y. The payoff function (1) can be rewrite as:

$$\tilde{f}(z, y) = f(z - y, y) = B(z - y) - D(z). \qquad (2)$$

In this case, the best-response correspondence of a country is denoted $Z(y)$. Our analysis then relies on the sign of the cross partial derivative of the payoff function (2) with regard to y and

[9] The choice variable can also be modelled as abatement. Nonetheless even if both choices are strategically equivalent, the game in abatement requires a roundabout way to the game in emissions to check for consistency (Diamantoudi and Sartzetakis, 2006).

[10] This argument is originally the one of Selten (1970). Formally, this monotone transformation of countries' payoff function lets us check Topkis Theorem conditions (Theorem A1 in Appendix A), keeping identical the properties of the equilibrium set.

z. If we note Δ_{ZY} this derivative, its sign (positive or negative) lets us split the analysis into two distinct cases: if $\Delta_{ZY} > 0$, then z and y are complementary (best-responses are upward sloping); if $\Delta_{ZY} < 0$, z and y are substitutable (best-responses are downward sloping). In the first case it means that there exists reinforcement effect between countries strategies; the higher the aggregated emission level of the $(n-1)$ other countries, the higher the emission level z of the country under consideration. In the second case, the higher the emission level y, the lower the global emissions z (keeping in mind the constraint $z \geq y$).

Given$\tilde{f}(z,y)$, $\Delta_{ZY} = -B''(z-y)$. Both are defined on the set $\varphi = \{(z,y): y \geq 0, z \geq y\}$. Because of the linear relationship between x, y and z, the sign of Δ_{ZY} is directly linked to the shape of the benefit function: either strictly concave or strictly convex. The object of the analysis is to define, in each case, the properties of the best-response correspondences, i.e. the existence and the static comparative properties of equilibria. For this purpose, the assumption H_0 below will be in effect throughout all the paper:

> Assumption H_0: Both functions $B: R^+ \to R^+$ and $D: R^+ \to R^+$are twice continuously differentiable and strictly increasing in their respective argument.

This assumption is not the most general.[11] Nonetheless differentiable functions allow us to simplify the exposition without losing any economic interpretations. Moreover, as Nash equilibria are not necessarily unique, we define X^*, Y^*, Z^* and F^* as respectively, the set of equilibrium emission levels for one country, the set of equilibrium emission levels of the $(n-1)$ other countries, the set of equilibrium global emissions and finally, the set of equilibrium individual payoffs. When the equilibrium point is unique we use the corresponding lower-case letter. The minimum and maximum elements of a set, when they exist, are underlined and highlighted. For example, $\underline{Z}^*$ and $\overline{Z}^*$ are respectively the lowest and the highest equilibrium global emission levels of the set Z^*. The same notations are adopted for the other equilibrium sets X^*, Y^* and F^*.

3. Characterization of the solutions in the non-cooperative case

In this section we characterize the set of Nash equilibria of the global emission game, i.e. when each country maximises its own payoff given the strategy adopted by the others. This scenario is known as the purely non-cooperative framework or status quo. The analysis is split into two: strategic interactions between countries are either globally complementary ($\Delta_{ZY} > 0$ on φ) or globally substitutable ($\Delta_{ZY} < 0$ on φ). This section relies on the property that the set of equilibria of a non-cooperative game coincides with the set of fixed-points of the vector of individual best-response correspondences (Lemma A.2_Topkis, 1998). We thus have to check if the latter has fixed-points.

3.1 The global complementarity case

When Δ_{ZY} is strictly positive on the set φ, countries' benefits functions are concave, meaning that the benefits countries have of their own emissions increase at a decreasing rate. This assumption reflects deceasing returns to scale in the activities of production or decreasing

[11] The central assumption to establish our result is that countries' payoff functions have increasing or decreasing differences in (z,y) (Topkis, 1978). A definition of this property is provided in appendix A (Definition A.1). In the differentiable case, this assumption coincides with the sign, respectively positive or negative, of the second cross partial derivative of the objective-function (Lemma A.1).

marginal utility in the consumption of produced goods.[12] In this case, the first proposition establishes a general result of existence relying on a direct application of the theorems presented in Appendix A.

Proposition 1:
If Δ_{ZY} is strictly positive on the set φ, then the global emission game has at least one symmetric pure-strategy Nash equilibrium and no asymmetric one.

A characteristic of the games with strategic complementarities is that they always possess at least one pure-strategy Nash equilibrium even if payoff functions are not quasi-concave in their argument. The intuitions behind this first result are the following:

i) As soon as the benefit function is strictly concave, the best-response correspondence of each country is increasing in its argument (Theorem A.1_Topkis, 1978), i.e. any solution $Z(y)$ of the maximisation problem (2) is increasing in y. The existence of equilibria then relies on Tarski's fixed-point theorem (Theorem A.2_Tarski, 1955). So, independently of the shape of the damage function, the global emission game always has at least one pure-strategy Nash equilibrium as soon as marginal benefits of emissions are decreasing.
ii) With the assumption of symmetry, we show that a country's best-response is always to pollute as much as each of the $(n - 1)$ other countries. A second property of the best-response correspondence is that if the latter possesses a fixed-point, then it's a symmetric equilibrium point.
iii) Given the relationship between x and z (i.e. $z = x + y$), any particular selection in the set of individual best-response correspondences of a country $X(y)$ has a slope strictly larger than -1.

To characterize further the set of equilibria, we need to specify the form of the damage function. In fact the latter determines the nature of the interactions at the individual level (contrary to the benefit function that characterizes the interactions at the global level). In this purpose, two independent subsets of conditions are provided through Propositions 2 and 3.

Proposition 2:
In addition to $\Delta_{ZY} > 0$ on φ, if the damage function is convex, then the individual best-response correspondence $X(y)$ is decreasing in y and there exist only one pure-strategy Nash equilibrium.

With a convex damage function, the harms caused to the environment because of global emissions increase at an increasing rate. The underlying idea is that the auto-purification capacity of environmental systems decreases at higher contamination levels. Nonetheless we do not consider here the case in which the system would collapse because of global emissions.

As a consequence of Proposition 1, a country individual best-response correspondence $X(y)$ is non-empty and has a slope larger than -1. The convexity of the damage function is then a sufficient condition for $X(y)$ to be decreasing in y. The slope of the individual best-response correspondence has thus 0 as an upper bound. It means that a country chooses its emission level as low as the one of the $(n - 1)$ other countries is high.

[12] If the benefit function is interpreted as the opportunity cost of abatement, the concavity reflects that abatement policies require increasingly sophisticated and costly technologies with the level of effort undertaken; or, in other words, decreasing returns in abatement technologies.

Assumptions of Proposition 2 are in fact the traditional ones in the global emission game: a concave benefit function and a convex damage function, together insuring a concave payoff function and continuous individual best-responses. Another important property is the existence of unique pure-strategy Nash equilibrium. Because of these nice properties, the assumptions of Proposition 2 are the most frequent in the literature studying the stability of international environmental agreements. The fact remains that when $\Delta_{\mathrm{ZY}} > 0$ on φ another case is conceivable: the one where $X(y)$ is increasing in y. To our knowledge this case has not yet been exploited in the literature.

Proposition 3:
In addition to $\Delta_{\mathrm{ZY}} > 0$ on φ, if the damage function is strictly concave, then the maximal and minimal selections of the individual best-response correspondence $X(y)$ are strictly increasing in y and there exists at least one pure-strategy Nash equilibrium.

When the damage function is strictly concave, the cross partial derivative of $f(x, y)$ with regard to x and y is strictly positive. Consequently the individual best-response of a country $X(y)$ is strictly increasing in its argument and has in particular a higher and a smaller element, respectively denoted by $\overline{X}(y)$ and $\underline{X}(y)$ (Theorem A.1_Topkis, 1978). In that respect a country will choose an emission level as high as the one of the others is high. The existence of a higher and a smaller equilibrium point is a direct consequence of Tarski's fixed-point theorem (Theorem A.2_Tarski, 1955).

Under the assumptions of Proposition 3, the set of equilibria also possesses a noteworthy order property: as the global emission game is a game of negative externality, the payoffs are the highest (the lowest) when countries coordinate on the lowest (the highest) equilibrium emission levels. In other words, the smallest equilibrium $\underline{X}^*$ is Pareto superior, whereas the highest equilibrium $\overline{X}^*$ is Pareto inferior (Theorem A.3_Milgrom and Roberts, 1990).

Three additional remarks can be made:

i) The multiplicity of equilibria is directly linked to the increasing individual best-response correspondences. Nonetheless this necessary condition is not sufficient: the slope of the individual best-responses must also be bigger than one in at least one equilibrium point (Cooper, 1999, p. 21).

ii) As a corollary of the previous remark, the equilibrium point can be unique in a game with strategic complementarities. An easy way to check this property is to have continuous best-responses with a slope everywhere less than one. This point is of particular interest to study the formation of international environmental agreement under strategic complementarities (Heugues, 2012).

iii) Given the linearity relation between the variables of the model ($z = x + y$), if the global emission game presents strategic complementarities in (x, y), it must be the case in (z, y). The assumptions on the benefit and damage functions are redundant or say in other words, if the damage function is concave, the benefit function must be concave as well. If not, the evolutions of equilibrium individual and global emission levels would go in incompatible directions. This point is further developed in the next subsection.

Further economic interpretations:

The idea of complementarity in the global emission game means that a country has a higher utility of the increase of its activity of consumption and production, the higher the global activity level of the others. The existence of reinforcement effects thus induces always higher emissions both at individual and global levels. This idea relies on a particular form of diffusion of consumption and production paths between countries and is made conceivable because of the globalization of economic activities (World Trade Organization, 1999; UNEP, 2012). Hence international trade liberalization has led to a greater scale of economic activities, stimulating the production of goods and services, consumption and transportation services (Copeland and Taylor, 2005).[13]

The kind of complementarity postulated in Proposition 3 lies on the less usual assumption that damages increase at a decreasing rate with global pollution. Yet, if the total costs of climate change represents the effects of increased climate variability and the costs of adaptation to the new climatic conditions, this approach has proved to be more coherent with the stylized belief that damage will remain relatively small (i.e. there will be no economic disruption) and better takes into account inertia of energy systems (Dumas and Ha Duong, 2005).[14]

The existence of reinforcement effects between countries' strategies can lead to a multiplicity of stable economic situations. Countries can thus coordinate on different economic activity levels. Nonetheless, in a purely non-cooperative context, the highest levels generate the strongest externalities and lead to the lowest welfare levels: payoffs are Pareto-ordered and inverse related with the levels of emissions. A first step to cooperation between countries could be to coordinate on the lowest emission levels.

The next subsection is devoted to the case of globally substitutable strategies. Now, best-response strategies evolve in opposite directions: a country chooses a higher global emission level for lower aggregated emissions of the $(n-1)$ other countries. This condition underlines a case where countries face strong national scale economies.

3.2 The case of global substitutability

When Δ_{ZY} is strictly negative on the set φ, emission levels *z* and *y* vary in opposite direction: the country under consideration will choose *z* as low as the aggregated emission level of the $(n-1)$ other countries is already high. Here best-response correspondences are strictly decreasing with the aggregated strategy of the others. Yet, in this case there is no general fixed-point theorem for games with more than two players: decreasing best-response correspondences do not necessarily imply that the game has an equilibrium point. To insure this existence we have to formulate stronger assumptions; to carry out the analysis we also have to check for the global consistency of the game imposed by the linear relationship between variables. We can distinguish two scenarios: the first is inspired from the natural monopoly theory: only one country is polluting; the second requires imposing a stronger assumption for existence of a symmetric Nash equilibrium in the *N*-country game.

The convex benefit function supports the idea that countries enjoy economies of scale in their activities of production: the mean production cost of a country decreases with the level of its activities. In this framework the first scenario relies on an economic efficiency principle that the global production should be realised by one country rather than shared among several. Considering the *N*-country global emission game, we can thus establish the existence of an

[13] In international trade theory the effect at hand is known as the scale effect. Nonetheless the latter comes up against competition from the technique effect, i.e. a trade liberalization that raises the scale of economic activity will also lower the dirtiness of production techniques. The full environmental impact can only be resolved through careful empirical investigation.

[14] See Heugues (2012) for further support of such an assumption in the global emission game.

equilibrium point such that one country is polluting whereas the $(n-1)$ others emit 0. This set-up is extended to the case where $m < n$ countries have strictly positive emissions denoted x_m and the best-response of the $(n-m)$ others is to pollute 0.

The second scenario is such that the n countries are active. A sufficient condition for existence of a pure-strategy Nash equilibrium in the *N*-country game is to assume quasi-concave payoff functions. This assumption guaranties continuous best-response functions and then the existence of an interior solution. To establish this result, we define $\bar{y}$ as the aggregated emissions threshold of the $(n-1)$ countries beyond which the country under consideration chooses not to pollute. This threshold is such that it equalizes marginal benefit and marginal damage for $x = 0$. In other terms $\bar{y} = D'^{-1}(B'(0))$ with $\bar{y} > 0$.

Proposition 4 establishes the conditions of existence of a Nash equilibrium for each scenario. In each case, we show that the equilibrium point is unique.

Proposition 4:
If Δ_{ZY} is strictly negative on the set φ, then the damage function is necessarily strictly convex and we check the three following points:

a. *For any $m < n$, if a symmetric Nash equilibrium for the game with m countries exists, then it's unique (to a permutation of the countries) and such that each of the m countries emits x_m, whereas the $(n-m)$ other countries emit nothing. In particular, if one country only emits ($m = 1$), then the game with n countries always admits one pure-strategy Nash equilibrium.*
b. *If the individual payoff function f(x, y) is strictly quasi-concave in x for all $y \in [0, \bar{y}]$, then there exists only one symmetric pure-strategy Nash equilibrium.*
c. *No other pure-strategy Nash equilibrium than the ones determined at point a) and b) exists.*

The negative sign of Δ_{ZY} has several consequences: first of all, individual best-response correspondences $X(y)$ are strongly decreasing with a slope upper bounded by -1. It means that if one country undertakes to reduce its individual emissions, the other $(n-1)$ countries will increase their own emissions such that totally cancelling the initial effort undertaken. This framework has been studied in particular by Hoel (1991), i.e. when the unilateral implementation of abatement policies by a subgroup of countries leads to a higher global emission level.

Second, if the game has strategic substitutability at the global level, this property has also to be true at the individual level because of the linear relationship between the variables. Formally, this constraint requires the strict convexity of the damage function.[15]

Finally the convex benefit function is the expression of strong economies of scale at the national level. Unlike Proposition 3, these scale effects are proper to each country and do not diffuse. In such a case, the competition between countries is very strong and can be such that activities are limited to a subset of them.

Whatever the nature of the interactions between countries, it's possible to establish conditions under which the global emission game holds Nash equilibria. The fundamental element is the slope of the best-response correspondence $Z(y)$. The next section is devoted to the static comparative properties of these equilibria with regard to two exogenous parameters: the

[15] Because $z = x + y$, if x is strongly decreasing in y, then z must be decreasing in y as well.

number of countries involved in the game and the perception they have of the seriousness of the problem.

4. Parametric properties of non-cooperative solutions

In this section we are interested in the static comparative properties of the equilibria with regard to the exogenous parameters of the model. These properties differ according to the set of assumptions defined above. Note that when the set of equilibria has more than one element, the static comparative properties will be true only for the smallest and the highest element. When the game has strategic complementarities, these properties are easy to provide thanks to a theorem by Milgrom and Roberts (Theorem A.5_Milgrom and Roberts, 1990). When strategies are strong substitutes, two contradictory effects are in place. We then rely on another argument provided by Sobel (Theorem A.4_Sobel, 1988) and under which the conclusions of Theorem A.5 are true.

4.1 Impact of the number of countries involved in the problem

We first study the impact of the number of countries involved in the environmental problem. The consequences in terms of pollution are not the same when considering 2 or 200 countries. The scale of the problem will thus influence individual and global emission levels as well as countries' payoff. The fundamental question here is: how the number of the other countries affects a country's strategic behaviour? In this section we determine how evolve equilibrium emission levels and payoffs when the number of countries increases.

Formally, the underlying parameter does not appear explicitly in a country's payoff function. Consequently the static comparative results are established using the structural properties of the game and the assumption of symmetric countries becomes fundamental. Proposition 5 below establishes the static comparative properties of the non-cooperative equilibria when countries have globally strategic complementarities.

Proposition 5:
Under the assumptions of Proposition 1, the equilibria of the global emission game are such that:

a) *Maximum and minimum equilibrium aggregated emission levels of the* $(n-1)$ *other countries,* $\underline{Y}^*$ *and* $\overline{Y}^*$*, are strictly increasing in n;*
b) *Maximum and minimum equilibrium global emission levels,* $\underline{Z}^*$ *and* $\overline{Z}^*$*, are strictly increasing in n*
c) *Maximum and minimum equilibrium payoffs,* $\underline{f}^*$ *and* $\overline{f}^*$*, are strictly decreasing in n.*

Under Proposition 1, there exists at least one symmetric Nash equilibrium point and no asymmetric one. Given Proposition 5, the latter is such that the larger is the number of interacting countries, the higher the aggregated and the global emission levels. Moreover if multiple, equilibria are Pareto ordered with the smallest equilibrium point $\underline{X}^*$ being Pareto superior. Nonetheless we cannot conclude here on the static comparative properties of equilibrium individual emissions levels. The latter rely on the form of the damage function. Both cases are tackled through Propositions 6 and 7. Note also that the larger the number of countries involved, the lower the welfare of each country. This relation is true whatever the nature of the interactions between countries; but, under the particular case of Proposition 5, this property is linked to the increased size of the global damages when *n* increases.

Proposition 6:
Under the assumptions of Proposition 2, the unique equilibrium point of the global emission game is such that the individual emission level x^* *is strictly decreasing in n.*

This proposal relies on the decreasing property of individual best-response functions. Hence the unique equilibrium point is such that individual emission levels are strictly decreasing with the number of countries involved. In other words, each country determines its activity level as low as the number of its partners is important. This conclusion relies on the idea of strategic substitutability at the individual scale that induces a certain degree of competition between countries. Nonetheless at the global scale, we always check that total emissions are increasing with *n*: global emissions increase with the number of interacting countries but less than proportionally.

Proposition 7:
Under the assumptions of Proposition 3, the set of equilibrium individual emission levels is such that the extreme selections $\underline{X}^*$ *and* $\overline{X}^*$ *are strictly increasing in n.*

Similarly, Proposition 7 relies on the increasing property of the individual best-response functions. In this case, there exists a multiplicity of Pareto ordered equilibria. The latter are such that a country has higher activity levels for larger numbers of interacting partners. This result is a direct consequence of the property of strategic complementarity observed at the individual scale. It can be interpreted as a phenomenon of emulation or of reinforcement between countries' strategies. At the global scale, we check that the global emissions increase more than proportionally with the number of countries involved.

Finally the next proposal establishes the static comparative properties of the non-cooperative solutions when strategies are globally substitutable. Contrary to the preceding cases, here payoff functions are decreasing with *n* because the size of the cake for each decreases with the increased number of countries.

Proposition 8:

a) *Under the assumptions of Proposition 4a), the asymmetric equilibrium point such that* $m < n$ *is invariant with* n*;*
b) *Under the assumptions of Proposition 4b), the symmetric equilibrium point is such that the equilibrium aggregated emission level of the* $(n - 1)$ *other countries* y^* *is strictly increasing in* n*, whereas equilibrium individual and global emission levels,* x^* *and* z^**, and the equilibrium welfare level* f^**, are strictly decreasing in* n*.*

Intriguingly here, the externalities because of the activities of consumption and production are not the stronger, the larger the number of countries involved. This conclusion raises the question of the relevance of this set of assumptions with regard to empirical observations.

Under the assumptions of Proposition 4, countries are involved in a strong competition in the fixation of their activity levels. In the first scenario in which only a subset of them has positive emissions, the others emitting 0, the equilibrium activity level is independent of *n*. The intuition is clear for the corner solution with one polluting country ($m = 1$) looking at its payoff function with its strategy as a sole argument. The same reasoning is true with *m* countries, $1 < m < n$, with strictly positive emissions.

In the second scenario, we are on the interior of the best-response functions, which are strongly decreasing. This implies that, at the equilibrium point, a country emission level is the lower, the larger the number of interacting countries. Finally, the decrease of the global emission level with n is because individual emissions levels decrease more than proportionally with n.

Further economic interpretations:

Except from Proposition 7, the results established in this section are in accordance with the ones of the economic theory presented through particular cases. Thus they constitute a substantial generalization of the existing static comparative results.

Because of its originality Proposition 7 calls for more comments. To our knowledge, the idea that countries could display strategic complementarity at the individual scale in their activities of consumption and production has not yet been exploited. In this respect, we can interpret countries as trading partners: the global emission level is then the higher, the larger the number of interacting countries. The intensification of trade relations between countries leads to increased global emissions, giving all its sense to the problem of GHG accumulation in the atmosphere. Relying on the international trade theory, trade liberalization generally leads to a higher global welfare for the countries involved in the process (even in the case of symmetric countries). With our model this point is observed through the increased benefits linked to the existence of reinforcement effects between countries strategies. Nonetheless this result is reversed taking into account the impact of human activities on the environment. Hence considering both the increased benefits and damages, the increased levels of activities do not necessarily lead to increased welfare levels. It remains that if countries are able to coordinate on lower emission levels, the process is welfare improving.

In the next subsection we consider the impact of the benefit-cost parameter. The latter expresses how countries balance the potential damages linked to climate change. We thus study the impact of such a parameter on countries' strategy and payoff.

4.2 Impact of the perception of the environmental damages

Another parameter appearing when exploiting the global emission game is the benefit-cost parameter generally denoted γ. It consists in considering the weight of the benefits linked to the polluting activities b relative to their costs c. $b > 0$ and $c > 0$ are thus two parameters generally weighted respectively the benefit and the damage functions and γ is defined as $\gamma = b/c > 0$. To establish our results, we consider the countries' payoff function $\tilde{f}(z, y, \gamma)$ defined on the set $\varphi = \{(z, y): y \leq z \leq y + K;\ \gamma > 0\}$ and with $\tilde{f}'_\gamma \geq 0$.

Considering the same approach as in the existing literature, we show that all equilibrium emission levels are increasing in γ. This claim is true whatever the nature of the interactions between countries. Nonetheless there is no clear cut static comparative result with regard to countries' payoffs for this parameter.

Proposition 9:
Assuming the payoff function $\tilde{f}(z, y, \gamma)$, the three following points are true:

a) *Under the assumptions of Proposition 1, maximum and minimum equilibrium emission levels, $\underline{Z}^*$ and $\overline{Z}^*$, $\underline{Y}^*$ and $\overline{Y}^*$, $\underline{X}^*$ and $\overline{X}^*$ are all increasing in γ;*
b) *Under the assumptions of Proposition 4a), equilibrium emission levels of the m active countries z_m, x_m and y_m are increasing in γ;*
c) *Under the assumptions of Proposition 4b), if the strategy set is ascending in γ, the unique symmetric Nash equilibrium is such that equilibrium emission levels z^*, x^* and y^* are increasing in γ.*

Whatever the set of assumptions defined above, if a country's strategy set is ascending in γ, then equilibrium individual, aggregated and global emission levels are all increasing in γ.

Even if this proposition seems trivial the proof relies on different properties of the game for each point, i.e. when countries present globally strategic complementarity or substitutability. Hence whatever the nature of the interaction, equilibrium emission levels are increasing in the benefit-cost ratio: the more a country weights the benefits of its economic activities relative to their environmental impacts, the larger its individual emissions. Alternatively, we can also say that the larger is γ, the more countries take care of the part of their payment that is independent of the strategy of the others. Yet the latter is increasing with the individual emission level. On the contrary, if the perception of the environmental damages increases relative to the opportunity cost of abatement (γ is decreasing), individual emission levels will be lower. The nature of the interactions between countries intervenes more when countries become sensitive to the strategy adopted by the others. In particular countries will be more reluctant to abate in the case of substitutable strategies.

To conclude on these results of static comparative, we can add that the way equilibrium emission levels and payoffs evolve rely also on the nature of the interactions between countries. These results suggest that countries will not be urged similarly with regard to the problem of GHG accumulation in the atmosphere and the increase of the environmental externalities. It's in particular the case when reinforcement effects exist between countries polluting activities. The assumptions on the benefit and the damage functions thus play an important role on the final issue of the game.

In the purely non-cooperative game, countries only consider two things in order to determine the level of their strategy: i) the strategy of the others and ii) the negative impact they bear because of their own emissions. Yet these externalities are also beard by the other countries. The resultant of the maximization of private interests is thus non optimal from a global point of view.

5. Conclusion

The analysis herein relies essentially on the sign of the second cross order derivative of payoff functions. By this way, we are able to provide an exhaustive presentation of all the possible interactions between countries and their consequences in terms of GHG accumulation in the atmosphere. These results thus form a typology of States' strategic behaviours in the case of a global externality such as the problem of climate change.

Through the implementation of environmental policies, countries behave strategically: one reason is that these policies determine in a sense their levels of activities and thus are at stake in their development and growth strategies. In the case of decreasing returns in the production activities ($B'' < 0$ or $\Delta_{ZY} > 0$), the global emission level can be all the higher as reinforcement effects between countries' strategies exist. When strategies are strongly complementary, each country determines its activity level as high as the one of the others is also high. A multiplicity of stable economic situations is then possible. Taking into account the impacts of human activities on the environment, a first step for countries should be to coordinate on the lowest individual emission levels, the latter inducing the higher payoffs.

Nonetheless, it's clear that even the Pareto superior non-cooperative equilibrium is not enough to provide the public good "environment" at a globally optimal level. Again countries determine too high individual emission levels when they do not consider the impact of their emissions on the others. Unfortunately, even if the globally optimal solution is the one leading to the highest aggregated payoff, it's not stable: we can show that each country individually has an incentive to deviate unilaterally. An extension of this paper would be to consider the profitability and stability of a partial agreement according to the nature of the interactions between countries.

Acknowledgements

This paper has benefited from fruitful comments from participants at SING 8 (Budapest, 2012). I'm particularly grateful to Francis Bloch and Sergio Currarini. This work has been achieved when I was working at the LAMETA (Montpellier, France) and has been revised and submitted as I'm a Marie Curie research fellow in FEEM (Milan, Italy).

References

Amir, R., (2005). Supermodularity and complementarity in economics: an elementary survey. Southern Economic Journal, 71, 636-660.

Amir, R. and V. Lambson (2000). "On the effects of entry in Cournot Markets". Review of Economic Studies, 67, 235-254.

Barrett, S. (1994). "Self-enforcing international environmental agreements", *Oxford Economic Papers*, 46, 878–894.

Barrett, S. (2003). *Environment and Statecraft: The strategy of Environmental Treaty-Making*, Oxford University Press, Oxford.

Carraro, C. and D. Siniscalco (1993), "Strategy for the international protection of the environment", *Journal of public Economics*, 52, 309-328.

Cooper, R. (1999). *Coordination games: complementarities and macroeconomics*, Cambridge University Press, Cambridge.

Copeland B. and S. Taylor (2005). "Free trade and global warming: a trade theory view of the Kyoto Protocol", *Journal of Environmental Economics and Management*, 49, 205-234.

Diamantoudi, E. and E. Sartzetakis (2006). "Stable international environmental agreements: an analytical approach", *Journal of Public Economic Theory*, 8, 247–263.

Dumas, P. and M. Ha-Duong (2005). An abrupt stochastic damage function to analyse climate policy benefits: essays on integrated assessment. In Haurie and Viguier (eds.), *The Coupling of climate and economic dynamics: essays on integrated assessment*, Springer Netherlands.

Finus, M. (2001). *Game Theory and International Environmental Cooperation*, New horizons in environmental economics, E. Elgar.

Heugues, M. (2012). "International environmental cooperation: a new eye on the greenhouse gas emissions control", *Annals of Operations Research*, DOI:10.1007/s10479–012–1156–8.

Hoel, M. (1991). "Global environmental problems: the effects of unilateral actions taken by one country", *Journal of Environmental Economics and Management*, 20, 55-70.

Milgrom, P. and J. Roberts (1990), "Rationalizability, learning and equilibrium in games with strategic complementarities", *Econometrica*, 58, 1255-77.

Milgrom, P. and J. Roberts (1994), "Comparing Equilibria", *American Economic Review*, 84, 441-59.

Pitlik H. (2007). A race to liberalization? Diffusion of economic policy reform among OECD-economies. *Public Choice*, 132,159-178.

Selten, R. (1970), *Preispolitik der mehr Produktenunternehmung in der statischen Theorie*, Springer Verlag, Berlin.

Sobel, M. (1988), "Isotone comparative statics for supermodular games", Working paper. SUNY at Stony Brook.
Tarski, A. (1955), "A lattice-theoretic fixed point theorem and its application", *Pacific Journal of Mathematics*, 5, 285-309.
Topkis, D. (1978), "Minimizing a submodular function on a lattice", *Operations Research*, 26, 305-21.
Topkis, D. (1998), *Supermodularity and Complementarity*, Princeton University Press, New Jersey.
UNEP (2012), *Global Environmental Outlook 5: Environment for the future we want*. United Nations Environment Programme.
World Trade Organization (1999). *Trade and the Environment*, special studies 4, accessible at: http://www.wto.org/english/res_e/reser_e/special_studies_e.htm.

Appendix A: Definitions and main theorems of lattice theory

Definitions and theorems introduced in this appendix are a simplified version of the original ones issued from lattice theory. We take the parameter and action sets, respectively T and X, to be compact subsets of the positive real, and X_t a correspondence from T to X, with X_t being the set of feasible actions when the parameter is t.

Definition A.1: *A function $f: X \times T \to R$ has [strictly] increasing differences in (x,t) if for all $x' \geq x$ and $t' \geq t$: $f(x',t') - f(x,t') \geq [>]\, f(x',t) - f(x,t)$.*

Lemma A.1 (see Amir 2005 for a proof): *If f is twice continuously differentiable, f has [strictly] increasing differences in (x,t) if and only if $\partial^2 f(x,t)/\partial x \partial t \geq [>]\, 0$ for all x and t.*

For functions defined on R^2, increasing differences is equivalent to supermodularity, so the two terms can be used interchangeably (Amir, 2005).

Definition A.2: *A function $f: X \to R$ is upper semi-continuous in x_0 if $\limsup_{x \to x_0} f(x) \leq f(x_0)$. A function f is upper semi-continuous if it is for all $x_0 \in X$.*

Definition A.3: *For $t \in R_+$, let $X_t = [g(t), h(t)] \subset R_+$, with $g(\cdot)$ and $h(\cdot)$ being real valued functions and with $g \leq h$. X_t is ascending [descending] in t if $g(\cdot)$ and $h(\cdot)$ are increasing [decreasing] in t.*

A non-cooperative game is a triple (N, X_i, f_i) consisting in a non-empty set of players N, a set of feasible individual strategies X_i, and a payoff function f_i defined on $\times_{i=1}^{i=n} X_i$ for each player i in N.

Definition A.4: *A non-cooperative game (N, X_i, f_i) is a supermodular game if each set X_i of feasible strategies is a compact set of the Euclidian space and if each payoff function $f_i(x_i, x_{-i})$ is upper semi-continuous in x_i and has increasing differences in (x_i, x_j) for all players $i, j \in N$ and $i \neq j$.*

Lemma A.2 (Topkis, 1998, chapter 4): *The set of all equilibrium points for a non-cooperative game (N, X_i, f_i) is identical to the set of fixed-points for the joint best-response correspondence, i.e. the direct product of players' individual best-response correspondences.*

Theorem A.1 (Topkis, 1978): *If $f: X \times T \to R$ is upper semi-continuous and has increasing [decreasing] differences in (x,t), and X_t is ascending [descending] in t, then the maximum and minimum selections of $x^*(t) = \arg\max_{x \in Xt} f(x,t)$ are increasing [decreasing] in t. If f has strictly increasing [decreasing] differences in (x,t), then the conclusion of the theorem holds for every selection of $x^*(\cdot)$.*

Theorem A.2 (Tarsky, 1955): *Let X be an non-empty and compact interval of the Euclidian space and let $f: X \to X$ be an increasing function ($f(x) \leq f(y)$ if $x \leq y$). Then the set of fixed-points of f is non-empty and contains a smallest and a largest element in X.*

Theorem A.3 (Milgrom and Roberts, 1990): *Let $\underline{x}$ and $\overline{x}$ denote the smallest and largest elements of X, and suppose y and z are two equilibria with $y \geq z$. (i) If $f_i(\underline{x}_i, x_{-i})$ is increasing in x_{-i}, then $f_i(y) \geq f_i(z)$. (ii) If $f_i(\underline{x}_i, x_{-i})$ is decreasing in x_{-i}, then $f_i(y) \leq f_i(z)$. If the condition in (i) holds for some subset of players N_1 and the condition in (ii) holds for the remainder $N \backslash N_1$, then $\overline{x}$ is the most preferred equilibrium for the players in N_1, and the least preferred for the remaining players. Similarly $\underline{x}$ is the least preferred by the players in N_1, and the most preferred by the remaining players.*

Theorem A.4 (Sobel, 1988): *Let X be an non-empty and compact interval of the positive real and let $f_t: X \to X$ a strictly increasing function $\forall t \geq 0$ and such that $f_t(x)$ is strictly increasing in t. Then the lowest and the highest fixed-point of f_t are strictly increasing in t.*

Theorem A.5 (Milgrom and Roberts, 1990): *For any $t \in T$ and T a partially ordered set, if the game is supermodular and if $f_i(x_i, x_{-i}, t)$ has increasing differences in (x_i, t) for each x_{-i}, then the smallest and the highest equilibrium points are increasing functions of t.*

Appendix B: Mathematical proofs

This appendix provides the proofs of the propositions made in the framework of the global emission game with N symmetric countries. The proofs of Propositions 1 to 4 are the consequence of the approach borrowed from Amir and Lambson (2000). The latter studies the case of a Cournot oligopoly. Our analysis differs with respect to the underlying objective-function, the issue at stake and the conclusions.

For the sake of our purpose, we assume that $B: R_+ \to R_+$ and $D: R_+ \to R_+$ are twice continuously differentiable and strictly increasing. Considering the payoff function$f(x,y) = B(x) - D(x+y)$, a country best-response correspondence is defined for any y, $0 \leq y \leq (n-1)K$, such that $X^*(y) = argmax_{x \in X} f(x,y)$. Similarly considering$\tilde{f}(z,y) = B(z-y) - D(z)$, the set of solutions of the maximization problem is $Z^*(y) = argmax_{z \in Z} \tilde{f}(z,y)$ defined on the strategy space is $\varphi = \{(z,y): y \leq z \leq y + K, 0 \leq y \leq (n-1)K\}$.
The existence of symmetric equilibria in the game relies on the definition of the joint best-response correspondence (Topkis, 1998). Because of the assumption of symmetric countries, the latter denoted *C(·)* is defined as follows:

$$C: y \to \frac{n-1}{n}(x' + y) \tag{B.1}$$

The variable x' is a country's best-response given the cumulated emissions of the $(n-1)$ other countries. As $x' \in [0, K]$ and $y \in [0, (n-1)K]$, it's easy to check that $\left(\frac{n-1}{n}\right)(x' + y) \in [0, (n-1)K]$. A fixed-point of *C(·)* is thus a symmetric Nash equilibrium such that $y_0 = (\frac{n-1}{n})(x'_0 + y_0)$ with $x'_0 = y_0/(n-1)$: a country chooses its emission level as high as the one of each of the $(n-1)$ other countries. Then the purpose of Propositions 1 to 4 is to establish the conditions of existence of fixed-points of *C(·)*.

Proof of Proposition 1:

- First we show that there exists at least one symmetric pure-strategy Nash equilibrium:

The proof relies on a direct application of Theorems A.1 and A.2. When $\Delta_{ZY} > 0$, a country's payoff function $\tilde{f}$ is upper semi-continuous and has strictly increasing differences in (z,y) on the set φ. Any selection of $Z^*(y)$ is thus increasing in y. As $Z^*(y) = x' + y$, it's equivalent to say that any selection of the joint best-response correspondence *C(·)* defined by equation (B.1) is also increasing in y. Given Tarski's fixed-point theorem we conclude that *C(·)* has a fixed-point which is a symmetric Nash equilibrium.

- Second we show that there is no asymmetric equilibrium point:

When $\Delta_{ZY} > 0$, Theorem A.1 lets us conclude that any selection of $Z^*(y)$ is increasing in y. To show that there is no asymmetric equilibrium, it's enough to show that $Z^*(y)$ is strictly increasing in y, i.e. for any $z' \in Z^*$, $\exists! y$ such that $z' = x' + y$ with z' being a best-response to y. By contradiction, suppose that there exists $\tilde{z} \in Z^*$ such that $\tilde{z}(y_1) = \tilde{z}(y_2)$ with $y_1 < y_2$. If $\tilde{z}(y_1)$ and $\tilde{z}(y_2)$ are interior solutions of the maximization problem of $\tilde{f}(z,y) = B(z-y) - D(z)$, both check the first order conditions:

$$B'(\tilde{z}(y_i) - y_i) - D'(\tilde{z}(y_i)) = 0, i = 1,2$$

As $\tilde{z}(y_1) = \tilde{z}(y_2) = z$, it follows that:
$B'(z - y_1) - D'(z) = B'(z - y_2) - D'(z)$,
And: $$B'(z - y_1) = B'(z - y_2). \quad \text{(B.2)}$$
As $\tilde{z}$ is strictly increasing in y, $\tilde{z}(y) = z$ is true for any $y \in [y_1, y_2]$. Equation (B.2) is then true for any y belonging to this interval. Considering the limit of (B.2) when $y_2 \to y_1$, we have:
$$\lim_{y_2 \to y_1} \frac{B'(z - y_1) - B'(z - y_2)}{y_2 - y_1} = 0. \quad \text{(B.3)}$$
(B.3) is equivalent to $B'' = 0$, which is in contradiction with $\Delta_{ZY} > 0$ on φ. Hence $\tilde{z}$ is strictly increasing and there is no asymmetric equilibrium point.□

Proof of Proposition 2:
When $\Delta_{ZY} > 0$ and the damage function is convex, the best-response correspondence $X(y)$ is an increasing function of y and there exists a unique pure-strategy Nash equilibrium.

- We first show that the slope of $X(y)$ belongs to the interval $]-1,0]$:

Given Proposition 1, $\Delta_{ZY} > 0$ implies that any selection of $Z^*(y)$ is strictly increasing in y, i.e. $Z'(y) \geq 0$. As $Z^*(y) = X(y) + y$, any selection of $X(y)$ has a slope larger than -1: $X'(y) = Z'(y) - 1 \geq -1$.
When the damage function is convex, $f(x, y)$ has decreasing differences in (x, y):
$\frac{\partial^2 f(x,y)}{\partial x \partial y} = -D''(x + y) \leq 0.$
Hence, the extreme selections of $X(y)$ are decreasing in y (Theorem A.1): $X'(y) \leq 0$.
As a whole, the slope of any selection of $X(y)$ belong to $]-1,0]$. The continuity of the best-response function is linked to the fact that any best-response with a slope lower bounded cannot jump down. Yet, $X(y)$ being decreasing in y implies that it doesn't have jump up and so no jump at all. Under the assumptions of Proposition 2, a country best-response is a continuous function.

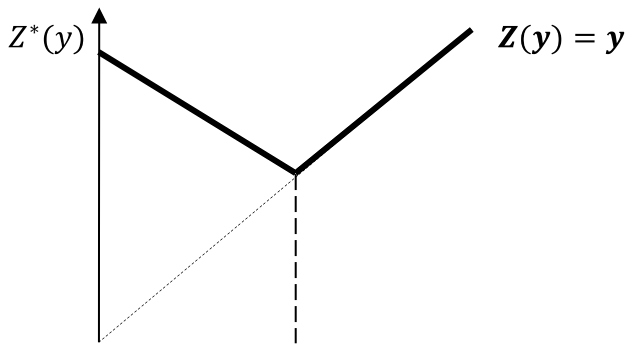
- We then show that the equilibrium is unique:

By contradiction, suppose two fixed-points z^1 and z^2 such that $z^1 = \sum_i x_i^1 \geq \sum_i x_i^2 = z^2$ (a). As any selection of $Z(y)$ is strictly increasing in y, this assumption implies that $y^1 \geq y^2$ (b). Yet, as $X(y)$ is decreasing in y, the inequality (b) implies that $x^1 \leq x^2$. Consequently, as countries are symmetric, $\sum_i x_i^1 \leq \sum_i x_i^2$ (c) and as $Z(y)$ is strictly increasing in y, $y^1 \leq y^2$ (d). Combining conditions (a), (b), (c) and (d) implies that $x^1 = x^2$. Under the assumptions of Proposition 2, the Nash equilibrium of the game is unique.□

Proof of Proposition 3:
When $\Delta_{ZY} > 0$ and the damage function is strictly concave, the proof of existence is a direct application of Theorems A.1 and A.2. When the damage function is strictly concave the payoff function $f(x, y)$ has strictly increasing differences in (x, y). Then best-response correspondences are non-empty and minimal and maximal selections of $X(y)$, $\underline{X}^*$ and $\overline{X}^*$, are strictly increasing in y. Then Tarski's fixed-point theorem ensures the existence of at least one fixed-point and thus of one pure-strategy Nash equilibrium in the global emission game.□

The proof of Proposition 4 requires an intermediate result expressed through Lemma B.1. This lemma establishes that if $\Delta_{ZY} < 0$ and as soon as the graph of $Z^*(y)$ does not intersect the first diagonal, any selection in the set $Z^*(y)$ is strictly decreasing in y. Subsequently, once $Z^*(y)$ intersects the first diagonal, both coincide. Figure B.1 below provides an illustration. The proof of the lemma is the one of Amir and Lambson (2000) adapting the notations to the global emission game.

Lemma B.1 (Amir and Lambson, 2000):
Under the assumptions of Proposition 4, any selection of $Z^*(y)$ is strictly decreasing in y for $y \in [0, y_0]$, with $y_0 \geq 0$ and such that $y_0 \in Z^*(y_0)$; and $Z^*(y) = \{y\}$ for $y > y_0$.



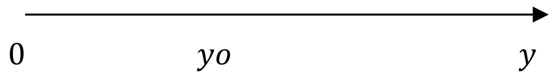


Figure B.1: Graph a selection of $Z^*(y)$ when $\Delta_{ZY} < 0$.

<u>Proof:</u>
i) First we show that any selection of $Z^*(y)$ is strictly decreasing in y:
As $\Delta_{ZY} < 0$, $Z^*(y)$ has strictly decreasing differences in (z, y). Yet the set of accessible strategies $[y, y + K]$ is ascending and not descending in y as required for the application of Theorem A.1. Relying on the *Rectangle Monotonicity Property* (Amir and Lambson, 2000), we can nevertheless conclude that every selection of $Z^*(y)$ is strictly decreasing in y whenever its graph is contained in a rectangle that lies entirely in the strategy set φ. In other words, for $y_1 \geq y_2$ with $z_1 \in Z^*(y_1)$, $z_2 \in Z^*(y_2)$, if the four points (y_1, z_1), (y_1, z_2), (y_2, z_1) and (y_2, z_2) are contained in φ, then $z_1 \leq z_2$.

ii) We show that if $y_0 \in Z^*(y_0)$ for all $y_0 \geq 0$, then $Z^*(y) = \{y\}$ for $y > y_0$:
Once the graph of $Z^*(y)$ intersects the first diagonal at the point y_0, both coincide for every value $y > y_0$, i.e. $z = y$, for any $y > y_0$. The proof is established by contradiction. First, we can exclude all the values $z < y$ as the accessible strategy set for z is $[y, y + K]$ with $K > 0$. Consequently suppose that $z > y$ and assume that $\exists \tilde{y} > y_0$ with $\tilde{z} \in Z^*(\tilde{y})$ and such that $\tilde{z} > \tilde{y}$. As $y_0 \in Z^*(y_0)$, the maximum utility a country can get in response to y_0 is $\tilde{f}(y_0, y_0) = f(0, y_0)$. Yet, $f(\tilde{z} - \tilde{y}, y_0) > f(0, y_0)$ because by assumption (H_0) the benefit function is strictly increasing in the individual emission level: $B(\tilde{z} - \tilde{y}) - D(y_0) > -D(y_0)$ with $B(0) = 0$ and $B'(\cdot) > 0$. Hence $B(\tilde{z} - \tilde{y}) > 0$ and $f(\tilde{z} - \tilde{y}, y_0) > f(0, y_0)$ is in contradiction with $y_0 \in Z^*(y_0)$ since the strategy $(\tilde{z} - \tilde{y})$ in response to y_0 leads to a higher payoff. We can thus conclude $Z^*(y) = \{y\}$ for $y > y_0$.□

Proof of Proposition 4:
Proposition 4 identifies two independent conditions under which there exists a unique pure-strategy Nash equilibrium when $\Delta_{ZY} < 0$. The first condition is such that a country is polluting alone $(m = 1)$, the others choosing to emit nothing. The second option is to assume the strict quasi-concavity of the payoff functions $f(x, y)$ in x for any $y \in [0, \bar{y}]$ with $\bar{y} = D'^{-1}(B'(0)) > 0$.

- ❖ Proof of Proposition 4.a)

On the interval $[0, y_0]$, $Z^*(y)$ is strictly decreasing in y (Lemma B.1) and $Z^*(0)$ is well defined: in a game with substitutable strategies, if x^M is the emission level of a country when it is the sole to pollute, x^M is the highest emission level it can choose (of course we need to have $x^M < K$).
Moreover, considering the individual best-response correspondence, $X(y) = Z^*(y) - y$. Under the assumptions of Proposition 4.a) and given Lemma B.1, $Z'^*(y) \leq 0$ implying $X'(y) = Z'^*(y) - 1 \leq -1$. Let x_1 and x_2 be two points on the graph of $X(y)$, such that $x_1 \in X(y_1)$ and $x_2 \in X(y_2)$ with $x_1, x_2 > 0$. Then for any $y_1, y_2 \geq 0$, the slope of the straight line joining x_1 and x_2 is such that $(x_1 - x_2)/(y_1 - y_2) \leq -1$.
Nonetheless, if x^M is a country's equilibrium emission level when it is the sole to pollute, then we have to check simultaneously $x^M \in X(0)$ and $0 \in X(x^M)$, i.e. others' best-response must also be not to pollute. By definition $x^M \in X(0)$ is true. To show that $0 \in X(x^M)$, we proceed by contradiction. Suppose x'$\in X(x^M)$ such that $x' > 0$. We thus have:

$$\frac{x' - x^M}{x^M - 0} = \frac{x'}{x^M} - 1 > -1. \qquad \text{(B.4)}$$

Equation (B.4) contradicts the fact that every selection in $X(\cdot)$ has a slope below -1. Thus $0 \in X(x^M)$.
The proof when $m > 1$ is identical. Nonetheless, the existence of an equilibrium point has to be assumed. The reason is that best-responses are strongly decreasing and without quasi-concave payoff functions, *C(·)* is not necessarily defined. If *C(·)* is defined and if it possesses a fixed-point, then the latter is the only one symmetric Nash equilibrium.

- ❖ Proof of Proposition 4.b)

In this case we have to show that if a country's payoff function is strictly quasi-concave in x, then $X(y)$ is a continuous function such that $X(y) > 0$ for any $y \in [0, \bar{y}]$ with $\bar{y} = D'^{-1}(B'(0)) > 0$; and $X(y) = 0$ for any $y > \bar{y}$.
Quasi-concavity of the payoff function $f(x, y)$ implies the continuity of $X(y)$. Yet $X(y)$ decreases at a rate larger than 1 in absolute terms (as a consequence of Lemma B.1), from the highest emission level x^M to 0.

- First we show that $0 \in X(\bar{y})$. The first order condition of the maximisation problem $max_x f(x, \bar{y})$ is $B'(x) - D'(x + y) \leq 0$. This condition is also sufficient to have a global maximum given the quasi-concavity of $f(x,y)$ in x. As $D'(\bar{y}) = B'(0)$, $x = 0$ satisfies the first order condition with equality. Hence $\bar{y}$ is the lowest level of y for which $X(y) = 0$. Moreover, as $Z^*(y) = \{y\}$ for $y > y_0$, $X(y) = 0$ for any $y \geq \bar{y}$.

- Then we show that there exists only a unique and symmetric Nash equilibrium. A Nash equilibrium is symmetric if and only if $y = (n-1)x$ fulfill$X(y) = y/(n-1)$: a country's best-response is to pollute as much as each of the $(n-1)$ others. Given the previous point, $X(\cdot)$ and $y/(n-1)$ intersect for any $n \geq 2$. Now uniqueness is the consequence that both functions are respectively decreasing and increasing in y for the values of y previously defined.

❖ Proof of Proposition 4.c)

If there is another equilibrium point than the ones established in point a) and b) of Proposition 4, then the latter is necessarily asymmetric. By contradiction, suppose the vector $(x^1, x^2, \dots, x^n)$ of equilibrium individual emission levels with $z = \sum_i x^i$ the global emission level. An equilibrium point is asymmetric if at least to countries choose different and strictly positive individual emission levels, i.e. suppose $x^1 > x^2 > 0$ with y^i such that $x^i = X(y^i)$, $i = 1,2$. By definition, we have $x^1 + y^1 = x^2 + y^2 = z$, with $y^1 < y^2$ as $x^1 > x^2$. The latter is in contradiction with $Z^*(y)$ strictly decreasing in y when $Z^* > 0$. Hence, there is no asymmetric equilibrium.□

Proof of Proposition 5:

❖ Proof of Proposition 5.a)

We first show that $\underline{Y}^*$ and $\overline{Y}^*$, are strictly increasing in n. The proof relies on Theorem A.4. Given Theorem A.1, the extreme selections of the joint best-response correspondence, $\underline{C}$ and $\overline{C}$, exist and are strictly increasing in y. As $(n-1)/n$ is strictly increasing in n, $\overline{C} = \frac{n-1}{n}(x' + y)$ is strictly increasing in $n, \forall y$. Given Theorem A.4, the highest fixed-point of $\overline{C}, \overline{Y}^*$ is strictly increasing in n. The proof with $\underline{C}$ is identical and $\underline{Y}^*$ is also strictly increasing in n.

❖ Proof of Proposition 5.b)

We show that $\underline{Z}^*$ and $\overline{Z}^*$, are strictly increasing in n. Under the assumptions of Proposition 1, the variables z and y are complementary, i.e. every selection in the set $Z^*(y)$ is strictly increasing in y. As $\overline{Y}^*$ is strictly increasing in n, $\overline{Z}^*$ is also strictly increasing in n. The argument is the same for the selection $\underline{Z}^*$.

❖ Proof of Proposition 5.c)

Finally we show that $\underline{f}^*$ and $\overline{f}^*$, are decreasing in n. Pollution being a negative externality, a country's payoff function is strictly decreasing in y. The highest payoff coincide with the lowest emission levels. As $y = (n-1)x$, $\underline{f}^*$ and $\overline{f}^*$ are equilibrium payoffs that correspond respectively to $\overline{X}^*$and $\underline{X}^*$. Hence, $\overline{f}^*$ is a country's payoff function which react optimally to $(n-1)\underline{X}^*$. The reasoning is the same for $\underline{f}^*$. Let X_n and f_n be the equilibrium individual emission level and the equilibrium payoff when n countries are interacting in the global emission game. Then we check:

$$\overline{f}_n = B(\underline{X}_n) - D(n\underline{X}_n) = B(\underline{X}_n) - D(\underline{X}_n + (n-1)\underline{X}_n)$$

Given the definition of a Nash equilibrium:

$$B(\underline{X}_n) - D(\underline{X}_n + (n-1)\underline{X}_n) \geq B(\underline{X}_{n+1}) - D(\underline{X}_{n+1} + (n-1)\underline{X}_n)$$

The latter inequality tells us that $\underline{X}_{n+1}$ is not a best-response to$(n-1)\underline{X}_n$. Moreover, as $(n-1)\underline{X}_n = Y_n < Y_{n+1} = n\underline{X}_{n+1}$ regarding point a) of Proposition 5, we also check:

$$B(\underline{X}_{n+1}) - D(\underline{X}_{n+1} + (n-1)\underline{X}_n) > B(\underline{X}_{n+1}) - D(\underline{X}_{n+1} + n\underline{X}_{n+1})$$

In other words, this inequality relies on the fact that $\underline{Y}_n$ is strictly increasing in n and $\overline{f}_n$ is decreasing in $\underline{Y}_n$. Now:

$$B(\underline{X}_{n+1}) - D(\underline{X}_{n+1} + n\underline{X}_{n+1}) = B(\underline{X}_{n+1}) - D\left((n+1)\underline{X}_{n+1}\right) = \overline{f}_{n+1}$$

Thus we can conclude that $\overline{f}_n > \overline{f}_{n+1}$. Using $\overline{X}_n$, we establish the proof for $\underline{f}_n$.□

Proof of Proposition 6:

With the convexity of the damage function, individual payoff functions $f(x,y)$ have decreasing differences in (x,y). Extreme selections of $X(y)$ are thus decreasing in y. As the equilibrium point is unique (Proposition 2), the unique selection x^* is such that $x^* = X(y^*)$. As x^* is decreasing in y^* and that y^* is strictly increasing in n (Proposition 5.a)), x^* is strictly decreasing in n. Consequently x^* and y^* evolve in opposite direction when n increases.□

Proof of Proposition 7:

With the strict concavity of the damage function, individual payoff functions $f(x, y)$ have strictly increasing differences in (x, y). Extreme selections of $X(y)$ are thus strictly increasing in y (Proposition 3). As $\overline{X}^* = X(\overline{Y}^*)$ and $\underline{X}^* = X(\underline{Y}^*)$ and as $\overline{Y}^*$ and $\underline{Y}^*$are strictly increasing in n (Proposition 5.a)), individual emission levels $\overline{X}^*$ and $\underline{X}^*$ are strictly increasing in n. Thus $\overline{X}^*$ and $\underline{X}^*$ evolve in the same direction as $\overline{Y}^*$ and $\underline{Y}^*$ as n increases.□

Proof of Proposition 8:

a) Under the assumptions of Proposition 4.a), the pure-strategy Nash equilibrium is such that m countries choose a positive emission level whereas the other $(n - m)$ countries choose to emit nothing. Consequently, individual emissions levels are invariant in n.

b) Under the assumptions of Proposition 4.b), we first show that y^* is strictly increasing in n whereas x^* and z^* are strictly decreasing in n using the definition of the joint best-response correspondence (equation B.1). As $(n - 1)/n$ is strictly increasing in n, $C(y)$ is strictly increasing in n $\forall y$. Given Theorem A.4, the unique fixed point of $C(\cdot)$ y^* is thus strictly increasing in n.
In addition, the solution set $Z^*(y)$ is strictly decreasing in y (*Rectangle Monotonicity Property*, see the proof of Proposition 4). Hence, y^* strictly increasing in n implies that z^* is strictly decreasing in n.
Similarly, $x^* = X(y^*)$ and $X(\cdot)$ is strictly decreasing in y (as soon as the solution is interior). y^* strictly increasing in n thus implies that x^* is strictly decreasing in n.
Finally we have to show that the equilibrium payoff is strictly decreasing in n. The proof is similar to the one of Proposition 5.c) without the bars as the equilibrium is unique:

$$f_n = B(x_n) - D(nx_n) = B(x_n) - D(x_n + (n-1)x_n)$$

Given the definition of a Nash equilibrium:

$$B(x_n) - D(x_n + (n-1)x_n) \geq B(x_{n+1}) - D(x_{n+1} + (n-1)x_n)$$

The inequality tells us that x_{n+1} is not a best-response to $(n-1)x_n$. Moreover, as $(n-1)x_n = y_n < y_{n+1} = nx_{n+1}$ regarding point a) of Proposition 8, we also check:

$$B(x_{n+1}) - D(x_{n+1} + (n-1)x_n) > B(x_{n+1}) - D(x_{n+1} + nx_{n+1})$$

In other words, this inequality relies on the fact that y_n is strictly increasing in n and f_n is decreasing in y_n. Now:

$$B(x_{n+1}) - D(x_{n+1} + nx_{n+1}) = f_{n+1}$$

Thus we can conclude that $f_n > f_{n+1}$.□

Proof of Proposition 9:

We have to show that, whatever the assumptions on the benefit and the damage functions, all equilibrium emission levels are always increasing with the benefit-cost parameter γ. Nonetheless the proof relies on different theorems depending on the nature of the interactions between countries. In particular there is no general static comparative result when countries' strategies are substitutable, except under particular conditions in the frame of symmetric games.

a) Under the assumptions of Proposition 1 ($\Delta_{ZY} > 0$ on φ), the global emission game is supermodular and $\tilde{f}(z, y, \gamma)$ has increasing differences in (z, γ) as soon as the benefit function is increasing in its argument:

$$\frac{\partial^2 \tilde{f}(z,y,\gamma)}{\partial z \partial \gamma} = cB'(z - y) > 0. \quad \text{(B.5)}$$

Under these conditions, the lowest and the highest equilibria of the game are increasing in γ (Theorem A.5). Consequently, $\underline{Z}^*$and $\bar{Z}^*$ are increasing in γ. Given the linear relationship between the variables of the game, i.e. $Y^* = (n-1)Z^*/n$ and $X^* = nZ^*$, we can conclude that $\underline{Y}^*$and $\bar{Y}^*$ and $\underline{X}^*$and $\bar{X}^*$ are also increasing in γ.

b) Under the assumptions of Proposition 4.a), $\Delta_{ZY} < 0$ on φ and the game is submodular. We establish the proof that z_m, x_m and y_m are increasing in γ when $m = 1$ and using Theorem A.4. In fact the payoff function of the country under consideration is increasing in x,$\forall \gamma$, and increasing in γ, $\forall x$:

i) $\partial f(x^M, \gamma)/\partial \gamma = cB(x^M) > 0$,

ii) $\partial f(x, \gamma)/\partial x > 0, \forall x \in [0, x^M]$.

If the second inequality were not checked, the equilibrium would be such that no country would pollute. Hence the equilibrium emission level of the country under consideration is increasing in γ. Considering m polluting countries, emission levels y_m and z_m are increasing in γ given the linear relationship between the variables (see point a) of the proof).

c) Under the assumptions of Proposition 4.b), $\Delta_{ZY} < 0$ on φ and payoff functions are quasi-concave. In this case we rely on Theorem A.1 (Topkis, 1978) to establish the proof that all emission levels are increasing in γ.
As countries are symmetric and the equilibrium is unique, we can rewrite the individual payoff function as a function of x and γ:

$$f(x^*, \gamma) = c[\gamma B(x^*) - D(nx^*)]. \quad \text{(B.6)}$$

Equation (B.6) has increasing differences in (x, γ) as $\frac{\partial^2 \tilde{f}(x,\gamma)}{\partial x \partial \gamma} = cB'(x) \geq 0$ is always true. If the strategy set $X_\gamma = [0, K(\gamma)]$ is ascending in γ, then $x^*(\gamma)$ is an increasing function of γ. Finally, because of the linear relationship between the variables of the game, y^* and z^* are also increasing in γ (see point a) of the proof). □

NOTE DI LAVORO DELLA FONDAZIONE ENI ENRICO MATTEI

Fondazione Eni Enrico Mattei Working Paper Series

Our Note di Lavoro are available on the Internet at the following addresses:
http://www.feem.it/getpage.aspx?id=73&sez=Publications&padre=20&tab=1
http://papers.ssrn.com/sol3/JELJOUR_Results.cfm?form_name=journalbrowse&journal_id=266659
http://ideas.repec.org/s/fem/femwpa.html
http://www.econis.eu/LNG=EN/FAM?PPN=505954494
http://ageconsearch.umn.edu/handle/35978
http://www.bepress.com/feem/

NOTE DI LAVORO PUBLISHED IN 2013

CCSD	1.2013	Mikel Bedayo, Ana Mauleon and Vincent Vannetelbosch: Bargaining and Delay in Trading Networks
CCSD	2.2013	Emiliya Lazarova and Dinko Dimitrov: Paths to Stability in Two-sided Matching with Uncertainty
CCSD	3.2013	Luca Di Corato and Natalia Montinari: Flexible Waste Management under Uncertainty
CCSD	4.2013	Sergio Currarini, Elena Fumagalli and Fabrizio Panebianco: Games on Networks: Direct Complements and Indirect Substitutes
ES	5.2013	Mirco Tonin and Michael Vlassopoulos: Social Incentives Matter: Evidence from an Online Real Effort Experiment
CCSD	6.2013	Mare Sarr and Tim Swanson: Corruption and the Curse: The Dictator's Choice
CCSD	7.2013	Michael Hoel and Aart de Zeeuw: Technology Agreements with Heterogeneous Countries
CCSD	8.2013	Robert Pietzcker, Thomas Longden, Wenying Chen, Sha Fu, Elmar Kriegler, Page Kyle and Gunnar Luderer: Long-term Transport Energy Demand and Climate Policy: Alternative Visions on Transport Decarbonization in Energy Economy Models
CCSD	9.2013	Walid Oueslati: Short and Long-term Effects of Environmental Tax Reform
CCSD	10.2013	Lorenza Campagnolo, Carlo Carraro, Marinella Davide, Fabio Eboli, Elisa Lanzi and Ramiro Parrado: Can Climate Policy Enhance Sustainability?
CCSD	11.2013	William A. Brock, Anastasios Xepapadeas and Athanasios N. Yannacopoulos: Robust Control of a Spatially Distributed Commercial Fishery
ERM	12.2013	Simone Tagliapietra: Towards a New Eastern Mediterranean Energy Corridor? Natural Gas Developments Between Market Opportunities and Geopolitical Risks
CCSD	13.2013	Alice Favero and Emanuele Massetti: Trade of Woody Biomass for Electricity Generation under Climate Mitigation Policy
CCSD	14.2013	Alexandros Maziotis, David S. Saal and Emmanuel Thanassoulis: A Methodology to Propose the X-Factor in the Regulated English and Welsh Water And Sewerage Companies
CCSD	15.2013	Alexandros Maziotis, David S. Saal and Emmanuel Thanassoulis: Profit, Productivity, Price and Quality Performance Changes in the English and Welsh Water and Sewerage Companies
CCSD	16.2013	Caterina Cruciani, Silvio Giove, Mehmet Pinar and Matteo Sostero: Constructing the FEEM Sustainability Index: A Choquet-integral Application
CCSD	17.2013	Ling Tang, Qin Bao, ZhongXiang Zhang and Shouyang Wang: Carbon-based Border Tax Adjustments and China's International Trade: Analysis based on a Dynamic Computable General Equilibrium Model
CCSD	18.2013	Giulia Fiorese, Michela Catenacci, Valentina Bosetti and Elena Verdolini: The Power of Biomass: Experts Disclose the Potential for Success of Bioenergy Technologies
CCSD	19.2013	Charles F. Mason: Uranium and Nuclear Power: The Role of Exploration Information in Framing Public Policy
ES	20.2013	Nuno Carlos Leitão: The Impact of Immigration on Portuguese Intra-Industry Trade
CCSD	21.2013	Thierry Bréchet and Henry Tulkens: Climate Policies: a Burden or a Gain?
ERM	22.2013	Andrea Bastianin, Marzio Galeotti and Matteo Manera: Biofuels and Food Prices: Searching for the Causal Link
ERM	23.2013	Andrea Bastianin, Marzio Galeotti and Matteo Manera: Food versus Fuel: Causality and Predictability in Distribution
ERM	24.2013	Anna Alberini, Andrea Bigano and Marco Boeri: Looking for Free-riding: Energy Efficiency Incentives and Italian Homeowners
CCSD	25.2013	Shoibal Chakravarty and Massimo Tavoni: Energy Poverty Alleviation and Climate Change Mitigation: Is There a Trade off?
ERM	26.2013	Manfred Hafner and Simone Tagliapietra: East Africa: The Next Game-Changer for the Global Gas Markets?
CCSD	27.2013	Li Ping, Yang Danhui, Li Pengfei, Ye Zhenyu and Deng Zhou: A Study on Industrial Green Transformation in China
CCSD	28.2013	Francesco Bosello, Lorenza Campagnolo, Carlo Carraro, Fabio Eboli, Ramiro Parrado and Elisa Portale: Macroeconomic Impacts of the EU 30% GHG Mitigation Target
CCSD	29.2013	Stéphane Hallegatte: An Exploration of the Link Between Development, Economic Growth, and Natural Risk
CCSD	30.2013	Klarizze Anne Martin Puzon: Cost-Reducing R&D in the Presence of an Appropriation Alternative: An Application to the Natural Resource Curse
CCSD	31.2013	Johannes Emmerling and Massimo Tavoni: Geoengineering and Abatement: A 'flat' Relationship under Uncertainty

ERM	32.2013	Marc Joëts: Heterogeneous Beliefs, Regret, and Uncertainty: The Role of Speculation in Energy Price Dynamics
ES	33.2013	Carlo Altomonte and Armando Rungi: Business Groups as Hierarchies of Firms: Determinants of Vertical Integration and Performance
CCSD	34.2013	Joëlle Noailly and Roger Smeets: Directing Technical Change from Fossil-Fuel to Renewable Energy Innovation: An Empirical Application Using Firm-Level Patent Data
CCSD	35.2013	Francesco Bosello, Lorenza Campagnolo and Fabio Eboli: Climate Change and Adaptation: The Case of Nigerian Agriculture
CCSD	36.2013	Andries Richter, Daan van Soest and Johan Grasman: Contagious Cooperation, Temptation, and Ecosystem Collapse
CCSD	37.2013	Alice Favero and Robert Mendelsohn: Evaluating the Global Role of Woody Biomass as a Mitigation Strategy
CCSD	38.2013	Enrica De Cian, Michael Schymura, Elena Verdolini and Sebastian Voigt: Energy Intensity Developments in 40 Major Economies: Structural Change or Technology Improvement?
ES	39.2013	Nuno Carlos Leitão, Bogdan Dima and Dima (Cristea) Stefana: Marginal Intra-industry Trade and Adjustment Costs in Labour Market
CCSD	40.2013	Stergios Athanassoglou: Robust Multidimensional Welfare Comparisons: One Vector of Weights, One Vote
CCSD	41.2013	Vasiliki Manousi and Anastasios Xepapadeas: Mitigation and Solar Radiation Management in Climate Change Policies
CCSD	42.2013	Y. Hossein Farzin and Ronald Wendner: Saving Rate Dynamics in the Neoclassical Growth Model – Hyperbolic Discounting and Observational Equivalence
CCSD	43.2013	Valentina Bosetti and Elena Verdolini: Clean and Dirty International Technology Diffusion
CCSD	44.2013	Grazia Cecere, Susanna Mancinelli and Massimiliano Mazzanti: Waste Prevention and Social Preferences: The Role of Intrinsic and Extrinsic Motivations
ERM	45.2013	Matteo Manera, Marcella Nicolini and Ilaria Vignati: Futures Price Volatility in Commodities Markets: The Role of Short Term vs Long Term Speculation
ERM	46.2013	Lion Hirth and Inka Ziegenhagen: Control Power and Variable Renewables A Glimpse at German Data
CCSD	47.2013	Sergio Currarini and Francesco Feri: Information Sharing Networks in Linear Quadratic Games
CCSD	48.2013	Jobst Heitzig: Bottom-Up Strategic Linking of Carbon Markets: Which Climate Coalitions Would Farsighted Players Form?
CCSD	49.2013	Peter Coles and Ran Shorrer: Optimal Truncation in Matching Markets
CCSD	50.2013	Heinrich H. Nax, Bary S. R. Pradelski and H. Peyton Young: The Evolution of Core Stability in Decentralized Matching Markets
CCSD	51.2013	Manuel Förster, Michel Grabisch and Agnieszka Rusinowsk: Anonymous Social Influence
CCSD	52.2013	Nizar Allouch: The Cost of Segregation in Social Networks
ES	53.2013	Fulvio Fontini, Katrin Millock and Michele Moretto: Investments in Quality, Collective Reputation and Information Acquisition
ES	54.2013	Roberta Distante, Ivan Petrella and Emiliano Santoro: Asymmetry Reversals and the Business Cycle
CCSD	55.2013	Thomas Michielsen: Environmental Catastrophes under Time-Inconsistent Preferences
ERM	56.2013	Arjan Ruijs and Herman Vollebergh: Lessons from 15 Years of Experience with the Dutch Tax Allowance for Energy Investments for Firms
ES	57.2013	Luciano Mauro and Francesco Pigliaru: Decentralization, Social Capital and Regional Convergence
CCSD	58.2013	Alexandros Maziotis, Elisa Calliari and Jaroslav Mysiak: Robust Institutions for Sustainable Water Markets: A Survey of the Literature and the Way Forward
CCSD	59.2013	Enrica De Cian, Fabio Sferra and Massimo Tavoni: The Influence of Economic Growth, Population, and Fossil Fuel Scarcity on Energy Investments
CCSD	60.2013	Fabio Sferra and Massimo Tavoni: Endogenous Participation in a Partial Climate Agreement with Open Entry: A Numerical Assessment
ES	61.2013	Daniel Atzori: The Political Economy of Oil and the Crisis of the Arab State System
ERM	62.2013	Julien Chevallier and Benoît Sévi: A Fear Index to Predict Oil Futures Returns
CCSD	63.2013	Dominik Karos: Bargaining and Power
CCSD	64.2013	Carlo Fezzi, Ian J. Bateman, and Silvia Ferrini: Estimating the Value of Travel Time to Recreational Sites Using Revealed Preferences
ES	65.2013	Luca Di Corato, Michele Moretto and Sergio Vergalli: Long-run Investment under Uncertain Demand
ES	66.2013	Michele Moretto, Paolo Panteghini and Sergio Vergalli: Tax Competition, Investment Irreversibility and the Provision of Public Goods
CCSD	67.2013	Dennis Guignet and Anna Alberini: Can Property Values Capture Changes in Environmental Health Risks? Evidence from a Stated Preference Study in Italy and the UK
ES	68.2013	William Brock, Anastasios Xepapadeas and Athanasios Yannacopoulos: Adjustment Costs and Long Run Spatial Agglomerations
ES	69.2013	Sasan Bakhtiari, Antonio Minniti and Alireza Naghavi: Multiproduct Multinationals and the Quality of Innovation
CCSD	70.2013	Rafael González-Val and Fernando Pueyo: Trade Liberalisation and Global-scale Forest Transition
CCSD	71.2013	Elena Claire Ricci: Smart-Grids and Climate Change. Consumer adoption of smart energy behaviour: a system dynamics approach to evaluate the mitigation potential
CCSD	72.2013	Valentina Bosetti and Marco Maffezzoli: Taxing Carbon under Market Incompleteness
CCSD	73.2013	Francesco Silvestri, Stefano Ghinoi and Vincenzo Barone: Nautical Tourism, Carrying Capacity and Environmental Externality in the Lagoon of Marano and Grado

CCSD	74.2013	Herman R.J. Vollebergh and Edwin van der Werf: The Role of Standards in Eco-innovation: Lessons for Policymakers
ES	75.2013	Gérard Mondello: Ambiguous Beliefs on Damages and Civil Liability Theories
CCSD	76.2013	Roberto Antonietti and Alberto Marzucchi: Green Investment Strategies and Export Performance: A Firm-level Investigation
CCSD	77.2013	A.K.S. Chand, Sergio Currarini and Giovanni Ursino: Cheap Talk with Correlated Signals
CCSD	78.2013	Ebru A. Gencer: An Overview of Urban Vulnerability to Natural Disasters and Climate Change in Central America & the Caribbean Region
CCSD	79.2013	Libo Wu, Changhe Li, Haoqi Qian and ZhongXiang Zhang: Understanding the Consumption Behaviors on Electric Vehicles in China - A Stated Preference Analysis
ES	80.2013	Andries Richter and Johan Grasman: The Transmission of Sustainable Harvesting Norms When Agents Are Conditionally Cooperative
CCSD	81.2013	Jonathan Colmer: Climate Variability, Child Labour and Schooling: Evidence on the Intensive and Extensive Margin
ERM	82.2013	Anna Alberini, Will Gans and Charles Towe: Free Riding, Upsizing, and Energy Efficiency Incentives in Maryland Homes
CCSD	83.2013	Inge van den Bijgaart, Reyer Gerlagh, Luuk Korsten and Matti Liski: A Simple Formula for the Social Cost of Carbon
CCSD	84.2013	Elena Claire Ricci: An Integrated Assessment of Super & Smart Grids
CCSD	85.2013	Laura Diaz Anadon, Gregory Nemet and Elena Verdolini: The Future Costs of Nuclear Power Using Multiple Expert Elicitations: Effects of RD&D and Elicitation Design
CCSD	86.2013	Carlo Carraro, Massimo Tavoni, Thomas Longden and Giacomo Marangoni: The Optimal Energy Mix in Power Generation and the Contribution from Natural Gas in Reducing Carbon Emissions to 2030 and Beyond
ES	87.2013	Ho Fai Chan, Bruno S. Frey, Jana Gallus and Benno Torgler: External Influence as an Indicator of Scholarly Importance
CCSD	88.2013	Marianna Gilli, Susanna Mancinelli and Massimiliano Mazzanti: Innovation Complementarity and Environmental Productivity Effects: Reality or Delusion? Evidence from the EU
CCSD	89.2013	Adrien Vogt-Schilb and Stéphane Hallegatte: Marginal Abatement Cost Curves and the Optimal Timing of Mitigation Measures
ERM	90.2013	Lion Hirth: The Optimal Share of Variable Renewables. How the Variability of Wind and Solar Power Affects their Welfare-optimal Deployment
CCSD	91.2013	Massimiliano Mazzanti and Antonio Musolesi: Nonlinearity, Heterogeneity and Unobserved Effects in the CO2-income Relation for Advanced Countries
CCSD	92.2013	ZhongXiang Zhang: Energy and Environmental Issues and Policy in China
CCSD	93.2013	Giacomo Marangoni and Massimo Tavoni: The Clean Energy R&D Strategy for 2°C
CCSD	94.2013	Carlo Fezzi and Ian Bateman: The Impact of Climate Change on Agriculture: Nonlinear Effects and Aggregation Bias in Ricardian Models of Farm Land Values
CCSD	95.2013	Paolo D. Farah and Riccardo Tremolada: A Comparison Between Shale Gas in China and Unconventional Fuel Development in the United States: Health, Water and Environmental Risks
CCSD	96.2013	Florens Flues, Dirk Rübbelke and Stefan Vögele: Energy Efficiency and Industrial Output: The Case of the Iron and Steel Industry
CCSD	97.2013	Gregor Schwerhoff: Leadership and International Climate Cooperation
CCSD	98.2013	Francisco Alvarez and Francisco J. André: Auctioning vs. Grandfathering in Cap-and-Trade Systems with Market Power and Incomplete Information
CCSD	99.2013	Mattia Amadio, Jaroslav Mysiak, Silvano Pecora and Alberto Agnett: Looking Forward from the Past: Assessing the Potential Flood Hazard and Damage in Polesine Region by Revisiting the 1950 Flood Event
CCSD	100.2013	Carlo Orecchia and Ramiro Parrado: A Quantitative Assessment of the Implications of Including non-CO2 Emissions in the European ETS
CCSD	101.2013	Yaella Depietri, Lorenzo Guadagno and Margaretha Breil: Urban Watershed Services For Improved Ecosystem Management and Risk Reduction, Assessment Methods and Policy Instruments: State of the Art
ERM	102.2013	Magali Dauvin: Energy Prices and the Real Exchange Rate of Commodity-Exporting Countries
ERM	103.2013	Chiara Franco and Giovanni Marin: The Effect of Within-Sector, Upstream and Downstream Energy Taxes on Innovation and Productivity
CCSD	104.2013	Francesco Bosello and Enrica De Cian: Climate Change, Sea Level Rise, and Coastal Disasters. A Review of Modeling Practices
ES	105.2013	L. Sella, G. Vivaldo, A. Groth and M. Ghil: Economic Cycles and Their Synchronization: A Survey of Spectral Properties
ES	106.2013	Veronica Ronchi: The Dawn of Italian Industry in Argentina: Pirelli in Buenos Aires (1898-1910)
CCSD	107.2013	Svenja Hector: Accounting for Different Uncertainties: Implications for Climate Investments?
CCSD	108.2013	Mélanie Heugues: The Global Emission Game: On the Impact of Strategic Interactions Between Countries on the Existence and the Properties of Nash Equilibria