Environmental Agreements in a Two-level Dynamic Framework

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This paper addresses the issue of conflicts between countries who share a renewable natural resource using a two-level framework. Contrary to the usual modeling of countries as representative agents who sign an international treaty to protect the resource that they share, this research considers the existence of some interaction between different sort of consumers and firms within each country. It discusses the influence of both domestic characteristics (consumers´ preferences and firms´costs) and the presence of some national environmental policy on the resulting regional agreement. The international level is modeled as a dynamic game in which each government decides its domestic regulation. Agreements are viewed as the result of some sort of bargaining among countries. An important insight of this paper is the incorporation of a numerical simulation (for a linear-quadratic example) to depict the dynamics of the model. In particular, its main result is an estimation of the path of emissions with the optimum treaty and without any agreement (the Markov Perfect equilibrium of the game).

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I. Introduction

Environmental spillovers have been widely analyzed in the economic literature. They appear mainly as examples of failures of the market mechanism to achieve efficiency, the origin of that failure being the presence of real externalities. Several kinds of theoretical solutions to those problems have been devised. The most classical is perhaps the imposition of taxes and subsidies to correct prices for the distortion in such a way that private decisions result in a social optimum (Pigou, 1920). Another well-known interpretation is to identify the problem of externalities as the absence of markets and associated property rights (Coase, 1960). In that view, developing a market for the externality and letting the parties bargain with each other is optimal irrespective of the allocation of the property rights between victim and perpetrator (when property rights are "well-defined" and there are no "transaction costs").

Controversies exist between one line of thought and the other. Pigovian taxes are criticized mainly because they are informationally very demanding (the regulator is supposed to know all private information in order to decide the precise tax to correct the externality). The Coasian approach is reproved mainly because it does not consider that pecuniary externalities can persist (or even be created) while solving real externalities and because it is often the case that its main assumptions are violated). Beyond those discrepancies about which policy has to be followed, international environmental problems represent a particularly interesting situation since while there are alternative environmental policies which can be implemented domestically by national governments, when pollution generated in one country degrades the environment of other countries there is no authority that can directly intervene and bargaining is the only option.

This research deals basically with cases of renewable natural resources passing or forming the boundaries of countries in a region using a two-level framework. So, contrary to the usual modeling of governments as representative agents who sign an international treaty to protect a common resource, this paper considers there is also a domestic instance within each country (different types of firms and consumers interact). Then, the domestic level outcome is analyzed as the result of a dynamic game in which each government (taking other countries' pollution as given) decides a national regulation, while regional environmental agreements are viewed as the result of negotiations among countries. This way of modeling clarifies the link between the situation before negotiations begin (in particular, the countries domestic characteristics as consumers' preferences and firms' abatement costs, and the existence of national environmental policies), and the potential regional environmental agreements which may result.

In general, except for very limited functional forms, there are no explicit analytical solutions to dynamic problems. So, the other insight of this paper (of a more technical kind) is the incorporation of a numerical simulation to depict the dynamics of the model. In particular, its main result is an estimation of the path of emissions that countries should agree upon (and the resulting welfare levels), compared to the pollution's trajectories if they merely cope with each other while applying some domestic environmental policy, or the completely unregulated equilibrium.

The paper is organized in the following way. Part II contains a review of the literature on environmental cooperation between countries, studied in the framework of dynamic games. Part III presents a model to interpret different hypothetical situations which can derive in international environmental agreements. Part IV deals with a numerical exercise to illustrate the model. Finally, part V summarizes the main results.

II. Review of the Literature

In recent years, various authors have used the theory of repeated non-cooperative games to analyze economic behavior in cases of oligopolistic exploitation of common-property resources. The basis for that argument is the tragedy of the commons (Hardin, 1968) in a prisoner's dilemma game, which emphasizes the impossibility of cooperation between the parties because independent exploitative actions are a dominant strategy for all participants. If various governments agreed to maintain a given level of stock of a resource, then each government would have strong incentives to reduce its own stock, free-riding on their neighbors. However, by a repeated game argument (the Folk theorem), countries can reach efficient outcomes through mutual agreement. The idea is to design a treaty which makes credible to each country that future cooperation from the others will occur only if that country complies. Each country has then a choice: to lose the benefits of future cooperation in exchange for the short-run gain of cheating, or to comply with the agreement and profit from continuing cooperation.

One dissatisfying aspect of repeated games is that they are based on the assumption that the environment of the game does not change over time. However, in many economic applications there is a state variable which evolves along time (for example, the capital stock of the economy, the stock of reputation or goodwill, the stock of natural resources) changing the way in which the game is being played. To incorporate those features, it is therefore necessary to deal with state-dependent dynamic games. Strictly theoretical papers on those dynamic games are numerous[2]. In general, they focus on the study of state-space strategies for which the state variable summarizes the past play. The equilibrium concept most widely used in those games is the Markov Perfect Equilibrium, and is the profile of Markov strategies which gives a Nash equilibrium in every subgame. The most important papers are due to Sundaram (1989), Dutta (1995a), and Dutta and Sundaram (1993a, 1993b). In addition, Dutta (1995b) presents a Folk Theorem for these types of dynamic games.

There are also some papers which deal with more applied research involving dynamic game theory and environmental problems (a good review of them is Clemhout and Wan, 1990). The case more analyzed in that literature is fisheries, of which Levhari and Mirman (1980) is the most important reference[3]. It depicts the situation of two countries simultaneously fishing in the same sea as a dynamic game in which the number of fish available is the state variable and its evolution depends on how much fish is caught in each period. The authors show, for particular planner utility and fish's reproduction functions (which imply a closed analytical solution to the dynamic problem), the difference along time between the optimal evolution of the resource and the one arising from a Markov-Perfect equilibrium. Moreover, another line of publication on the same topic (e.g., Hämäläinen, Haurie and Kaitala, 1985), deals with the idea of using threats to sustain cooperation in fishery games.

Other problems involving natural resources studied in a dynamic game framework are air pollution (e.g., acid rain) and global warming effects. For the former, Tahvonen, Kaitala, and Pohjola (1993) compare the sustainability and cost-effectiveness of the 1997 agreement for a 50 % reduction of sulfur emissions in Finland and the former Soviet Union, with the alternatives under purely non-cooperative and fully optimal outcomes. Pallage (1995) performs a calibration for air pollution between Brazil and the US, which estimates the transfers necessary to achieve an optimum. For global warming, Martin, Patrick and Tolwinski (1993) analyze, within an asymmetric game of transboundary pollution,

[2] For a general review of dynamic games, see Fudenberg and Tirole (1991) or Basar and Olsder (1994).

[3] Kaitala's (1985) comprehensive survey of game theoretic models of fishery management also constitutes a key reference for applications to fisheries.

what are the effects of using a global carbon tax as a scheme of agreement where countries cooperate to set the level of that tax. For a similar problem, Beltratti (1995) discusses a linear-quadratic model where two countries share an environmental resource, emphasizing the positive correlation between the ratio of Markov equilibrium to efficient resource stocks, and the rate of time preference.

The main difference between this research and the existing literature is that countries involved in the negotiation are not modeled as representative agents but as governments whose aim is to maximize the welfare in their own country (defined as the sum of consumers' and producers' surpluses). Hence, before international negotiations, there is the possibility that each government had previously decided to impose national policies to influence consumers and firms' behavior towards the resource. Instead of viewing conflicts among countries in exactly the same way as a person to person situation, this approach adds another dimension and new possibilities for considering links between domestic regulations and international treaties. More precisely, it clarifies the extent to which previous domestic policies and the characteristics of consumers´s preferences and firms´ production technologies influence the type of international agreements which can be attained. Another insight is a numerical simulation that depicts the way in which the model works, even when the relevant functions are such that there are no closed solutions for the dynamic problem. The methodology utilized to perform the simulation is a variation of the method used in the real business cycle literature to solve social planning and recursive competitive equilibrium problems.

III. The Model

A simple modeling framework is employed to describe the situations involved in environmental conflicts: there is one common natural resource, one commodity (denoted by c or y according to if it is consumption or production of the good) in each country. Then, a few countries (i = 1,..,I) share the resource which is on (or crosses) their common political border. Each country has several types of consumers (indexed by h) and firms (indexed by f). There is a continuum of consumers and a continuum of firms of each type, but the number of types is finite. Each country consumes what it produces, so there is no international trade[4].

Consumers like the commodity, and value the stock of the resource they see. For example, if part of the boundary of two countries is constituted by a lake, a^i is the quality of the water that they see on the side of the lake that corresponds to country i. More precisely, each type of consumer has the following utility function: $U_h^i = v_h^i(c_h^i, a^i) - p^i \cdot c_h^i$, where c^i_h is the quantity consumed of the commodity by consumers of type h, and p^i is the price of the commodity, all in country i. The functions v^i_h are all increasing in consumption and resource quality, continuously differentiable and strictly concave[5]. On the other hand, each type of firm in country i chooses its level of production so as to maximize its profits. It also generates some pollution which affects the quality of the natural resource, and its objective function can therefore be written as: $\Pi_f^i = p^i \cdot y_f^i - TC_f^i(y_f^i, x_f^i)$, where y^i_f is the quantity of the commodity produced by firms of type f in country i, and x^i_f is the amount of pollution generated by

[4] There is an abundant literature about the link between trade and the environment. Environmental regulation is supposed to play a role in determining both the composition of trade and the pattern of investments. However, empirical research has not been able to confirm that opinion (see, for example; Tobey, 1990; Grossman and Krueger, 1991; or Jaffe et al, 1995).

[5] The main advantage of using this type of quasi-linear utility function is that consumers´s utility is represented in monetary terms and so it makes aggregation across individuals easier.

those firms. The functions TC^i_f are all continuously differentiable, strictly convex, and increasing in output.

Each country has a government whose aim is to maximize the welfare of its nation, defined as the sum of all domestic consumers' and firms' surpluses[6]. This is: $g^i = \sum_h s^i_h \cdot \left[v^i_h(c^i_h, a^i) - p^i \cdot c^i_h\right] + \sum_f r^i_f \cdot \left[p^i \cdot y^i_f - TC^i_f(y^i_f, x^i_f)\right]$, where s^i_h is the mass of consumers of type h and r^i_f is the mass of producers of type f. Finally, the resource involved is renewable (e.g., water). Its stock exhibits a natural growth (e.g., natural water cleansing through biodegradation of organic pollutants and precipitation of solids). That natural rate of amelioration is partially offset by the harm caused by polluters (in this case, firms). In general, $a^i_{t+1} = Z^i(a^i_t, \sum_f r^1_f \cdot x^1_{f,t}, ..., \sum_f r^I_f \cdot x^I_{f,t})$, where a^i_t and a^i_{t+1} are the states of the resource at country i in periods t and t+1, and the summations represent aggregate pollution levels in each country. This way of modeling pollution takes into account the fact that the damage to the resource depends not only on how much do firms pollute but also on where those pollutants are emitted, because harm may vary negatively with distance[7].

So, the model is one of a regional reciprocal externalities occur in which countries are both the polluter and the victim, as in the case of acid rain or pollution of common lakes and seas[8]. Then, the issues concerning equilibrium and efficiency for this model can be analyzed in two different levels: domestic and international. For the former, two main scenarios can be considered. First, there is an equilibrium without government intervention, which results from the free interaction among firms and consumers within each country. This is inefficient due to the presence of a unidirectional externality from producers to consumers (i.e., producers pollute a lake or river and domestic consumers are harmed). Second, there is a partially efficient equilibrium in which governments adopt some domestic policy measures: each country instruments an environmental policy taking the pollution of other countries as given. Full efficiency, however, requires further policy, because each government does not consider the harm that national firms impose on other countries. Solving that problem to some degree is the role played by an ideal international agreement (level I).

1) Domestic Situation (Level II)

i. Absence of any Environmental Regulation

When there is not any environmental regulation, and agents are price takers in the market of the commodity[9], each consumer in each country maximizes his intertemporal utility subject to his budget

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[6] This function assumes that the government is "benevolent", in the sense that its goal is not selfish or politically-oriented. Chapter 2 of my dissertation contains variations on this point, and also incorporates informational problems which arise in these kinds of situations.

[7] If pollutants were heterogeneous, such feature would be reflected by Z^i. Note that it could also be assumed (as is almost always the case in this literature) that the resource is common in a more complete sense: pollution from other countries affects the consumer in the same way as pollution in his own country. That simplification allows the use of a single stock variable, but it is less realistic in terms of how the problem is treated in actual regional environmental agreements.

[8] Previous versions of this paper included the case of unidirectional externalities but it was excluded here since it is just a special case easier to solve than the reciprocal externality one.

[9] To assume a Walrasian context for the market of the good is a reasonable hypothesis here, since there is a continuum of firms and consumers who cannot influence the price of the commodity.

constraint following this rule:

$$p^i = \frac{\partial v_h^i(c_h^i, a^i)}{\partial c_h^i}$$

Besides, each firm chooses production and pollution levels in order to maximize its intertemporal profits, such that:

$$p^i = \frac{\partial TC_f^i(y_f^i, x_f^i)}{\partial y_f^i} \quad \text{and} \quad \frac{\partial TC_f^i(y_f^i, x_f^i)}{\partial x_f^i} = 0$$

Proposition 1. In the unregulated equilibrium, firms and consumers interact in a Walrasian fashion in the market for the commodity by equating their marginal costs and marginal utilities to the price of the good, while *pollution is pursued by the firm until the marginal cost from its emissions is equal to zero*.

A particularity of these conditions is that, even when they care about it, consumers cannot control the state of the resource, so their problem is in fact static. In the same way, firms exercise control over the level of pollution that they generate, but the state of the resource has no influence on their payoff, so their problem is also static. Then (in each country) consumers and firms demand and supply the commodity, firms choose pollution levels and, as a result of these independent decisions and its natural growth, the resource evolves through time according to the function Z^i . Clearly, the unregulated equilibrium outcome within each country is inefficient, since neither the national nor the international damages to the resource are taking into account.

ii. Governments Apply some Domestic Environmental Regulation

As the unregulated equilibrium outcome within each country is inefficient, the attainment of efficiency requires some corrective measures. So, governments (which seek to maximize the welfare in each country: g^i) can establish some domestic environmental regulation. In that case, the problem becomes fully dynamic, since both the level of pollution and the quality of the resource are part of the intertemporal objective function of the government.

In this situation, each country cares about the other's past or futures actions only through their influence on the resource. Countries cope with each other in a passive, non-strategic way. The result of that interaction results in a Markov-Perfect equilibrium.

Definition 1. Defining the state vector as $b_t = (a_t^1, a_t^2, ..., a_t^I) \in B \equiv \Re_+^I$, a decision of country i as the set of functions: $d^i = \{c_h^i(b), y_f^i(b), x_f^i(b), p^i(b)\}_{\forall h,f}$ (where $d^i : B \to \Re^{h+2\cdot f+1}$) belonging to D^i (the set of decisions for country i), *a Markov best response R^i of government i to a decision function of the other governments ($\tilde{d}^{-i}$)* is a mapping $R^i : B \times D^{-i} \to D^i$ such that $R^i(b, \tilde{d}^{-i})$ solves:

$$V^i(b, \tilde{d}^j) = \max_{\substack{\{c_h^i, y_f^i, x_f^i, p^i\}_{t=o}^{\infty} \\ \forall f,h}} \left\{ \left[\sum_h s_h^i \cdot v_h^i(c_h^i, a^i) - \sum_h s_h^i \cdot p^i \cdot c_h^i + \sum_f r_f^i \cdot p^i \cdot y_f^i \right. \right.$$
$$\left. \left. - \sum_f r_f^i \cdot TC_f^i(y_f^i, x_f^i) \right] + \beta \cdot V^i(b', \tilde{d}'^j) \right\}$$

subject to $a'^i = Z^i(a^i, \sum_f r_{f,t}^1 \cdot x_{f,t}^1(b, \tilde{d}^{-i}), ..., \sum_f r_{f,t}^I \cdot \tilde{x}_{f,t}^I) = a'^i(b, d^i, \tilde{d}^{-i})$, $\tilde{d}^{-i}(b) = d^{-i}(b)$, and the non-negativity constraints, given an initial state of the resource (b_o).

As usual in infitite-horizon dynamic problems,the prime superscripts correspond to the situation in period t+1, and the discount factor $\beta \in (0,1)$ is assumed for simplicity to be the same for every country. V^i is the value function of each country, which reflects the maximized intertemporal value achieved by following the optimal decisions. Note that the value function V^i also depends on the state of the resource in the other countries (even if the government of country i does not control them) through its effect on domestic consumers' utility. Besides, looking at the present state of the resource in other countries can help a government to forecast what their future levels of pollution will be, which also have an influence on its intertemporal welfare.

Definition 2. A Markov Perfect equilibrium is an I-tuple of Markov decisions $(d^{1^*}(b), d^{2^*}(b),..., d^{I^*}(b))$ such that, for all i, $d^{i^*}(b) \in R^i(b, d^{-i^*}(b))$. Those decision rules are the emissions' policy functions.

In this framework, each government must find a way to induce its citizens to fulfill the following first order conditions (FOC):

for consumption (c^i_h); $$s_h^i \cdot \frac{\partial v_h^i(c_h^i, a^i)}{\partial c_h^i} = s_h^i \cdot p^i$$, for all h

for production (y^i_f); $$r_f^i \cdot p^i = r_f^i \cdot \frac{\partial TC_f^i(y_f^i, x_f^i)}{\partial y_f^i}$$, for all f

for price (p_i) ; $$\sum_h s_h^i \cdot c_h^i = \sum_f r_f^i \cdot y_f^i$$

These conditions correspond to the market of the commodity. Note that the FOC for p^i represents an equilibrium condition (production is equal to consumption), since p^i is in fact a Lagrange multiplier (the shadow price of the resource constraint). However, if markets are competitive as it is here, the government does not need to intervene at all in the market of the good, since the results shown are identical to the ones obtained through a Walrasian equilibrium.

Conversely, when the government wishes to implement the domestically optimal level of pollution, it cannot rely on a market outcome and has to design an explicit mechanism to be imposed to the other economic agents. One of the possible mechanisms consists of establishing *emission standards* for each type of firm[10]. In that case, the FOC for pollution is: $\mathrm{r}_\mathrm{f}^\mathrm{i} \cdot \frac{\partial \mathrm{TC}_\mathrm{f}^\mathrm{i}(\mathrm{y}_\mathrm{f}^\mathrm{i}, \mathrm{x}_\mathrm{f}^\mathrm{i})}{\partial \mathrm{x}_\mathrm{f}^\mathrm{i}} = \beta \cdot \frac{\partial \mathrm{V}^\mathrm{i}}{\partial \mathrm{a}'^\mathrm{i}} \cdot \frac{\partial \mathrm{Z}^\mathrm{i}}{\partial \mathrm{r}_\mathrm{f}^\mathrm{i} \mathrm{x}_\mathrm{f}^\mathrm{i}} \cdot \mathrm{r}_\mathrm{f}^\mathrm{i}$, for all f while the envelope condition is: $\frac{\partial V^i}{\partial a^i} = \sum_h \left[s_h^i \cdot \frac{\partial v_h^i(c_h^i, a^i)}{\partial a^i} \right] + \beta \cdot \frac{\partial V^i}{\partial a'^i} \cdot \frac{\partial Z^i}{\partial a^i}$. Combining the

[10] Note that, in this model, governments cannot set ambient limits (i.e., to allow a limited amount of pollution to accumulate on their borders) because that would imply choosing the level of pollution of firms which are located in other countries. But, as it will be analized below, they could set emission taxes, marketable permits, etc.

envelope and first-order conditions for pollution yields:

$$\frac{\dfrac{\partial TC^i_f}{\partial x^i_f}}{\dfrac{\partial Z^i}{\partial r^i_f x^i_f}} = \beta \cdot \frac{\dfrac{\partial TC^i_f}{\partial x'^i_f}}{\dfrac{\partial Z^i}{\partial r^i_f x'^i_f}} \cdot \frac{\partial Z^i}{\partial a'^i} + \beta \cdot \sum_h (s^i_h \cdot \frac{\partial v^i_h}{\partial a'^i}) \text{ , for all f}$$

Proposition 2. Under domestic environmental regulation the equilibrium conditions for emissions are such that *the marginal abatement cost of emissions equal the marginal loss (in terms of intertemporal utility for domestic consumers) that pollution generates through the deterioration of the resource.*

An alternative corrective mechanism would be to set Pigovian taxes (*emission charges*, t^i_f) [11]. This practice is very common in several countries. For example, emissions' charges for air pollution are used in Canada (British Columbia), France, Japan and Sweden. Taxes are also used for waste water effluents in several European countries as Germany or Belgium, and Canada (OECD, 1994). In this model, taxes should be designed in such a way that each firm is induced to behave optimally when it maximizes: $p^i \cdot y^i_f - TC^i_f(y^i_f, x^i_f) - t^i_f \cdot x^i_f$, and therefore decides according to the FOC: $p^i = \frac{\partial TC^i_f(y^i_f, x^i_f)}{\partial y^i_f}$ and $\frac{\partial TC^i_f(y^i_f, x^i_f)}{\partial x^i_f} = t^i_f$. Then, governments should equate the tax rate to the domestic marginal loss caused by pollution, and this implies that:

$$t^i_f = \left[\beta \cdot \frac{\dfrac{\partial TC^i_f}{\partial x'^i_f}}{\dfrac{\partial Z^i}{\partial r^i_f x'^i_f}} \cdot \frac{\partial Z^i}{\partial a'^i} + \beta \cdot \sum_h (s^i_h \cdot \frac{\partial v^i_h}{\partial a'^i}) \right] \cdot \frac{\partial Z^i}{\partial r^i_f x^i_f}$$

Another alternative is to limit emissions by deciding a quota on the total level of the externality ($\sum_f r^i_f \cdot x^i_f$) and distributing *tradable pollution permits* among firms. Then, the government could decide the path of the aggregate pollution, and firms could be allowed to trade them among themselves. This problem is the same as the one seen above, with the only difference that, instead of the sum of the cost for each type of firm, the government can use a global cost function defined as[12]:

$$TC^i(Y^i, X^i) = \min_{\{y^i_f, x^i_f\}_{t=o}^{\infty} \forall f} \left\{ \left[\sum_f r^i_f \cdot TC^i_f(y^i_f, x^i_f) \right] / \ \sum_f r^i_f \cdot y^i_f = Y^i, \ \sum_f r^i_f \cdot x^i_f = X^i \right\}$$

so that its problem becomes:

[11] In terms of efficiency, here, this is equivalent to assigning a quota of allowed emissions to the generator of the externality when there is complete information. However, when information is asymmetric, taxes and quotas are not substitutes (see Weitzman, 1974).

[12] Actual estimations of such cost functions exist. For example, those made for sulfur abatement by the Technical Research Center of Finland (Tahvonen, Kaitala, and Pohjola, 1993).

$$V^i(a^1,...,a^I) = \max_{\substack{\{c_h^i, Y^i, X^i, p^i\}_{t=o}^{\infty} \\ \forall h}} \left\{ \left[\sum_h s_h^i \cdot v_h^i(c_h^i, a^i) - \sum_h s_h^i \cdot p^i \cdot c_h^i + p^i \cdot Y^i - TC^i(Y^i, X^i) \right] + \beta \cdot V^i(a'^i, ...a'^I) \right\}$$

subject to $a'^i = Z^i(a^i, X^1,..., X^I)$ for all periods, given the initial state of the resource and providing the decision variables are non-negatives. The FOC for X^i is now: $\frac{\partial TC^i(Y^i, X^i)}{\partial X^i} = \beta \cdot \frac{\partial V^i}{\partial a'^i} \cdot \frac{\partial Z^i}{\partial X^i}$ and the envelope condition is exactly the same as before. The combined condition that the aggregate pollution for country i should satisfy is similar to the one above:

$$\frac{\frac{\partial TC^i}{\partial X^i}}{\frac{\partial Z^i}{\partial X^i}} = \beta \cdot \frac{\frac{\partial TC^i}{\partial X'^i}}{\frac{\partial Z^i}{\partial X'^i}} \cdot \frac{\partial Z^i}{\partial a'^i} + \beta \cdot \sum_h (s_h^i \cdot \frac{\partial v_h^i}{\partial a'^i})$$

This quasi-market mechanism of setting quotas is not a merely theoretical convenience but an actual policy used in environmental regulation, particularly in the United States. Examples involve emission trading under the Clean Air Act (see Hahn, 1989)[13], and regulation on water pollution at the states' level[14].

As a way to simplify the exposition, the rest of the analysis is made in terms of emission standards for each type of firms. But, regardless of the instrument chosen to regulate, the allowed emissions evolve through time as the resource changes. The resulting steady state for the resource at this level of analysis is higher than the one under an unregulated situation, because the government considers the positive effect of the resource quality on its consumers' utility. Beginning at the state of the resource without any policy, governments aim to follow a path of emissions which goes to the domestically optimal quality of the resource[15].

This implies that, when the new environmental regulation is instituted, there is a "jump" down in pollution and, when the resource begins to improve, policy measures for pollution become less tight.

[13] The Clean Air Act originally specified that no new emission sources would be allowed in regions which do not meet specified ambient standards. However, concerns that this prohibition would impact strongly on economic growth in those regions led the Environmental Protection Agency to institute the "offset rule", which consists of allowing new sources to locate in those areas provided that they offset their new emissions by reducing pollution from existing plants (by trade of permits). The CAA also instituted other mechanisms of tradable permits in the U.S.: "bubbles", netting" and "banking".

[14] The US regulation on water consists of a mix between effluent technology-based limitations and standards imposed through individual "National Pollutant Discharge Permits". However, in 1981, the state of Wisconsin implemented a marketable permits program to control pollution in the Fox River, mainly directed at waste generated by pulp and paper plants and for municipal waste treatment plants. In the state of Colorado, local authorities have issued restrictive limits for pollution from all sources, because their discharges were endangering drinking water supplies in the Dillon Reservoir. Colorado allowed point sources to increase their discharges if they acquired allowances from non-point sources. Similar experiments were conducted for the Tar-Pimlico watershed in North Carolina (Dudek, Stewart, and Wiener, 1994).

[15] This is what Chari and Kehoe (1990) call "the commitment version" in the sense that the government is assumed to have commitment technologies to bind its actions and those of future governments. Hence, the government sets a sequence of maximum allowed emissions once and for all at the beginning of time and then consumers and firms choose allocations in each subsequent time period. In the language of differential games, it is a "closed-loop" or "memoryless" strategy.

While the latter occurs, countries' welfare level increase until they attain the new steady state. To follow that policy function implies that the corresponding national intertemporal welfare (or value function V^i) are maximized. Those gains change according to the evolution of the resource until a steady state is attained.

2) International Situation (Level I)

Even if domestic regulations were successful and perfectly applied in every country, they would not by themselves lead to efficiency. Countries would tend to internalize the harm that their firms impose on their consumers, but they will not take into account the fact that they also affect other countries' consumers. Efficiency is not fully reached unless the sum of the welfare functions for every country is maximized. That could be possible if there were a supra-national authority who solved the following problem:

$$V(a^1,...,a^I) = \max_{\substack{\{c_h^i, y_f^i, x_f^i, p^i\}_{t=o}^{\infty} \\ \forall f,h,i}} \left\{ \sum_i \left[\sum_h s_h^i \cdot v_h^i(c_h^i, a^i) - \sum_h s_h^i \cdot p^i \cdot c_h^i + \sum_f r_f^i \cdot p^i \cdot y_f^i - \sum_f r_f^i \cdot TC_f^i(y_f^i, x_f^i) \right] + \beta \cdot V^i(a'^i, ... a'^I) \right\}$$

subject to one constraint for the resource at each border: $a'^i = Z^i(a^i, \sum_f r_f^1 \cdot x_f^1, ..., \sum_f r_f^I \cdot x_f^I)$ for all i, the non-negativity constraints, and given the initial state of the resource. This is again a dynamic programming problem because, even more than the national governments, the supra-national authority would be conscious that the resource can be depleted along time if it is not well managed.

The solution to this problem yields the same FOCs that were obtained in level II for the commodity consumed and produced in each country, but different ones for the emission decisions' variables for x^i_f; $r_f^i \cdot \frac{\partial TC_f^i(y_f^i, x_f^i)}{\partial x_f^i} = \beta \cdot \frac{\partial V}{\partial a'^1} \cdot \frac{\partial Z^1}{\partial r_f^i x_f^i} \cdot r_f^i + ... + \beta \cdot \frac{\partial V}{\partial a'^I} \cdot \frac{\partial Z^I}{\partial r_f^i x_f^i} \cdot r_f^i$ for all f in all I. The corresponding envelope conditions can be expressed as:

$$\frac{\partial V}{\partial a^i} = \sum_h \left[s_h^i \cdot \frac{\partial v_h^i(c_h^i, a^i)}{\partial a^i} \right] + \beta \cdot \frac{\partial V}{\partial a'^i} \cdot \frac{\partial Z^i}{\partial a^i} \qquad \text{, for all } a^i$$

Proposition 3. The attainment of fully efficient levels of pollution requires *the marginal abatement cost from domestic emissions to be equal to the intertemporal marginal loss that they generate for consumers in all the countries affected.*

Regulation by a supranational authority typically implies stricter emission standards than the ones decided domestically. To reach efficiency as established by a supranational planner, each country should follow a policy function for pollution (derived from the solution to the dynamic programming problem described above) which depends on the state of the resource at each border. Compared to the situations at level II, there is a "jump" down in the path of pollution, and then a new increasing trajectory until the optimal steady state for the resource is reached[16].

If each country followed that optimal policy, its intertemporal welfare would also depend on the level of the resource. Hence, values for the welfare of both countries would change as the resource evolves to the steady state. If the discount factor is equal to one, however, the welfare do not depend on the initial quality of the resource, because the time horizon is infinite. Therefore, if all periods are equally valued, most of the overall time "is spent" at the steady state, so it is not important which is the point of departure.

The discount factor being close to one allows efficiency to be depicted by a single frontier instead of a moving one[17]. Moreover, efficiency (as decided by a supra-national authority) is represented by a unique point of the utility possibility frontier, because of the use of a quasi-linear utility function. To reach other points on that frontier, a set of transfers is needed. Those transfers can take the form of direct financial transfers or favors in areas in which the countries have common interests. For example, it is possible that the US had agreed to build a desalinization plant on the Colorado River only to maintain good relations with Mexico (1973), and that the same spirit had leaded to the Columbia River Treaty between the United States and Canada (1961).

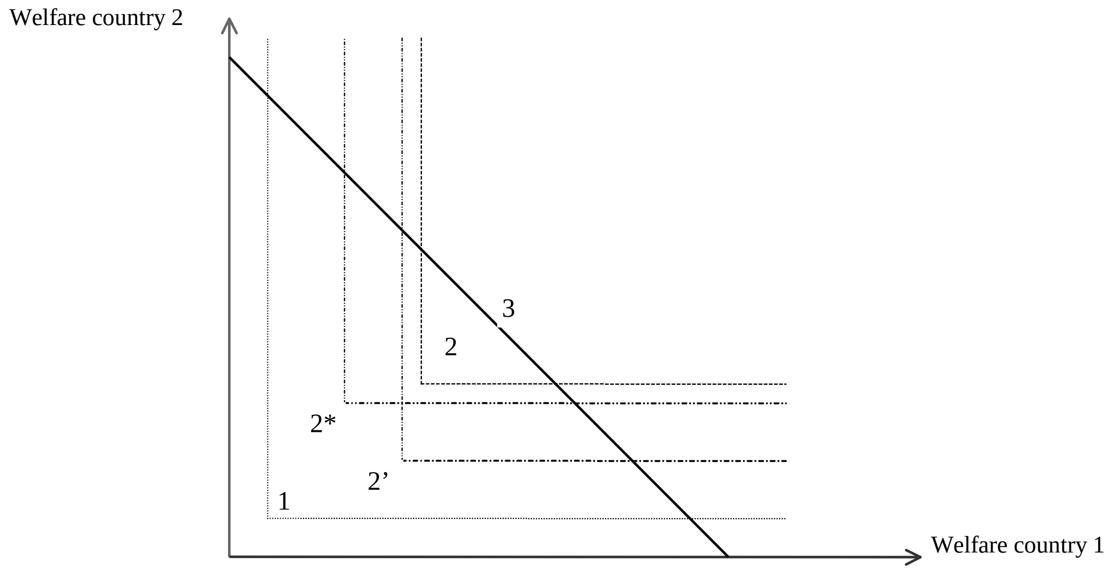
It is a fact that cooperation exists, because there are numerous international agreements on environmental problems[18]. However, the problem of international agreements is that there is not such thing as a supranational authority, so countries have to make some sort of arrangement among themselves if they want to improve upon the situation of level II. Moreover, governments can begin negotiations in different circumstances, and potential agreements may be strongly determined by that initial state of affairs, in addition to their consumers and firms characteristics (figure 1.).

[16] Pollution agreements usually prescribe a decrease in emissions linked to a time frame. For example, the Sulphur Protocol of the Geneva Convention on Long-Range Transboundary Air Pollution (1979) reduce emissions 50 % in a schedule with intermediate limits at the years 2000, 2005, and 2010. However, there are no rules for a sufficiently long time horizon in which countries can begin to relax emissions standards as the state of the resource improves.

[17] The discount factors also have an effect on the *shape* of the value function and the policy functions.

[18] In 1992, there were already a total of 885 legal international instruments which had provisions on environmental matters (Weiss, Szasz, and Magraw, 1992). In general, cooperation consists of agreement on different quantitative limits (e.g., for the Great Lakes, Canada and the US agree on maximum levels of pollution that the Lakes should have; in the Rhine chloride agreement, countries agree on concentrations measured at some points; and in air pollution agreements in Europe, they set goals about decreases in aggregate emissions).

Figure 1: Welfare for both countries at the two levels (symmetric case)



One possibility is that countries bargain in a situation where there exists no previous internal environmental policy (number 1 in figure 1). Another is that they are initially in a situation where all countries have already implemented optimal national environmental policies (number 2 in figure 1). The third and fourth cases arise when some countries have previous environmental policies and others have not (depicted in figure 1 as 2’ and 2^{*})[19]. From the observation of figure 1, it is clear that the space of negotiation is different if countries begin at point 1 than at point 2, and so is their outcome. One rationale associated to the different solutions which can be attained is thinking in terms of the repeated negotiation among countries. In the case of state-dependent dynamic games as this one, those solutions imply that governments follow certain previously agreed policy functions while the treaty is respected by every country, but switch to a different pollution path when a deviation is detected (Dutta, 1995b).

The idea is that when there is no supranational authority, the starting situation determines which are the countries’ individually rational payoffs. Hence, if countries have already some domestic environmental policies in place, there are some relatively less efficient agreements which will not be reached. Finally, as will be seen with the help of the numerical simulation, it may be that for certain combinations of consumers and firms (“very clean” countries versus “very dirty” countries) require the presence of transfers if there is to be a fully efficient environmental agreement.

IV. Numerical Application

This section deals with a numerical exercise designed to illustrate the model, performed using the computer program GAUSS. Its main characteristic is that it allows to simulate the policy functions

[19] Note that the assumption behind points 2’ and 2^{*} in figure 1 is that the increase in welfare resulting from higher consumer surplus but lower producer surplus in the country which implements a domestic environmental policy is higher than the resulting increase in the neighbor’s consumers utility due to that policy.

resulting from the two levels' problems (even if they have no closed solutions), instead of dealing solely with the steady states as is usual for dynamic problems in the literature. The present section states the methodology employed and the results obtained. As an illustration of the procedure, the computer program written for the simulation of level II is reproduced in Appendix A.

1) Information Necessary for the Simulation

The example assumes some specific forms for the utility and cost functions, for the law of motion of the resource and some arbitrary values for the parameters (also reproduced in Appendix A), which give rise to a linear-quadratic problem. To simplify the exposition, only two types of consumers, two types of firms, and two countries are considered. However, the program can be extended to more types.

The utility is different for each type of consumer but it does not depend on where they live. The function for each type of individual is: $v_h^i = A_h \cdot \ln c_h^i + B_h \cdot \ln a^i$, where the first and second term refer respectively to the preferences that each consumer has toward consuming the commodity and his taste for seeing the resource in a good state (e.g., clean water). A_h and B_h are both constants (A_h, B_h>0, A_h> B_h). Firms are assumed to have a cost function of the following form (which again varies among types but not among countries): $TC_f^i = \frac{1}{2} \cdot D_f \cdot {y_f^i}^2 + \frac{1}{2} \cdot (E_f \cdot y_f^i - x_f^i)^2$, where the constants D_f and E_f are both greater than zero. The quadratic term referring to pollution implies that the marginal cost from pollution is negative only if $E_f^i \cdot y_f^i > x_f^i$. Thus, less pollution increases costs as long as that inequality holds.

The resource evolves according to a certain "radioactive law" (Neher, 1990). That law is equivalent to assuming an exponential decay of the pollutant as a way to characterize the natural cleansing of the resource (for example, water bodies). Hence, firms in both countries pollute the resource but the latter also regenerates itself. The equation of movement of the resource in each border (derived in Appendix B) takes the following form:

$$a'^i = \bar{a}^i \cdot \delta + a^i \cdot (1-\delta) - \psi^{ii} \cdot \sum_f r_f^i \cdot x_f^i - \psi^{-ii} \cdot \sum_f r_f^{-i} \cdot x_f^{-i} ,$$

where $\bar{a}^i$>0 is the state of the resource at the border of the country i when there is absolutely no pollution, 0<δ<1 is its rate of natural cleaning, and the ψ's>0 determine how pollutants affect the resource at each border (given that they are transported from one country to the other). Note that the heterogeneous harm of the different kind of emissions is already incorporated in the x's, being the ψ's only indicators of transport. Since it does not matter which firm is polluting in a particular country (what is taken into account are total emissions), the so-called "transport matrix" can be illustrated by a 2x2 matrix with the elements in the diagonal of the matrix are greater, reflecting the larger effect of local emissions. The values of the parameters have been arbitrarily assumed here, but it is possible to find estimations for this kind of matrices in the environmental literature (e.g., for acid rain in Europe: Tahvonen, Kaitala and Pohjola, 1993 or Mäler, 1990).

In addition to the parameters of the transport matrix, the other values needed to calibrate the model are related to the utility functions, the cost functions and the masses of each type of consumers and firms. These values are chosen with the aim of reproducing a situation widely acknowledged by environmental negotiators: two asymmetric countries, one poor and the other rich, where in the former consumers and firms are less environment-oriented than in the latter. For the utility functions, it is assumed that type 1 consumers are more environmentally oriented than type 2 consumers, so they prefer to have a smaller consumption but a cleaner water (i.e., $A_1 < A_2$ and $B_1 > B_2$). That same criterion is used for the cost functions, where firms of type 1 are assumed to have better cleaning technologies than firms of type 2, even if they are equally efficient in other aspects of production (hence, $D_1 = D_2$ and $E_1 < E_2$)[20].

Since consumers and firms of the same type are equal among countries, the difference between countries has to rely on the masses of each type of consumers and firms that are at each location. Country 1 is supposed to be inhabited by a larger percentage of environmentally oriented consumers and cleaner firms than country 2. Finally, the discount factor is taken very close to 1, the rate of decay of pollutants (δ) is set at a particular value (not very large) and the value for the pristine state of the resource ($\bar{a}^i$) at both borders is also decided.

1) Methodology Employed at each Level

i. Steps for the Simulation of Level I

The methodology employed in this subsection follows the one used by the real business cycle literature (Hansen and Prescott, 1994) for social planning cases with the difference that the function to maximize consists of the sum of consumer and producers' surpluses in two countries. That distinction gives rise to two linear constraints embodied in the supranational planner's problem which correspond to the market-clearing conditions. In that sense, this simulation is very different from models of heterogeneous agents in the above mentioned macroeconomic literature (e.g., Ríos-Rull, 1994). Several steps are necessary to solve the dynamic programming problem:

♦ *Define the variables and the function to maximize*

There are 2 state variables (a_1 and a_2) and 14 decision variables (2 implicit prices or Lagrange multipliers, 4 consumptions, 4 productions, and 4 for emissions). The objective function is the sum of the welfare in both countries (g).

♦ *Define a matrix (C) for the laws of motion of the state variables*

In this case, C is a 3x20 matrix. The number of rows corresponds to one row for constant terms and two other rows for the equations of movement of each of the resources. The number of columns is determined by a column for constants, 2 for the state variables in period t, 14 columns for the decision variables, and 3 more columns for the constant and the state variables in period t+1.

♦ *Compute the steady states for all the variables from the FOC*

Using the FOC, each type of consumer in each country consumes the commodity, which for the functions utilized in this example corresponds to: $c_h^i = \dfrac{A_h}{p^i}$ for i = 1, 2 and h = 1, 2. Additionally, the FOCs for production of each type of firm in each country with the assumed functions are: $p^i = y_f^i \cdot [D_f + (E_f)^2] - E_f \cdot x_f^i$ for i = 1, 2 and f = 1, 2. The first-order conditions for pollution are: $x_f^i = E_f \cdot y_f^i - \psi^{ii} \cdot \beta \cdot \dfrac{\partial V}{\partial a'^i} - \psi^{i-i} \cdot \beta \cdot \dfrac{\partial V}{\partial a'^{-i}}$ for i = 1, 2 and f = 1, 2 while the envelope conditions can be expressed as: $\dfrac{\partial V}{\partial a^i} = \left(\sum_h \dfrac{s_h^i \cdot B_h}{a^i} \right) + \beta \cdot \dfrac{\partial V}{\partial a'^i} \cdot (1-\delta)$ for i = 1,2.

[20] This assumption is of course not necessary. It is made to isolate the effect of the environmental regulation on production.

Plugging the envelope conditions into each pollution FOC, and then into the FOC for production, it has to be true in the steady state that: $p^i = y_f^i \cdot D_f + E_f \cdot \frac{\beta}{1-\beta\cdot(1-\delta)} \cdot \left[\psi^{ii} \cdot \left(\sum_h \frac{s_h^i \cdot B_h}{a^i} \right) + \psi^{i-i} \cdot \left(\sum_h \frac{s_h^{-i} \cdot B_h}{a^{-i}} \right) \right]$ for i=1, 2 and f=1, 2. The formulas between brackets express the harm that national *and* foreign consumers suffer because of country i's pollution. Those brackets and their immediate precedent multiplicative term are denoted K^i. Production for the commodity can be expressed as: $y_f^i = \frac{p^i - E_f \cdot K^i}{D_f}$ for i = 1, 2 and f = 1, 2. Then, production by each type of firm in each country not only depends positively on prices but also on another term which contains the state of the resource. Hence, the efficient levels of emissions depend not only on the level of production, but also on the harm that production causes to all consumers in the region: $x_f^i = E_f \cdot y_f^i - K^i$ for i = 1, 2 and f = 1, 2.

Implicit prices in the steady state imply full employment of the resources from the point of view of the planner. Those Lagrange multipliers are the ones that allow the fulfillment of one market-clearing constraint in each country: $(p^i)^2 \cdot \left(\sum_f \frac{r_f^i}{D_f} \right) - p^i \cdot \left[\sum_f r_f^i \cdot \frac{E_f \cdot K^i}{D_f} \right] - \left(\sum_h s_h^i \cdot \frac{A_h}{p^i} \right) = 0$ for i=1,2. However, since both equations contain K^i (which are functions of the resource), they also depend on the a^i s . So, in order to determine the steady states for prices and resource levels (4 unknowns), two more equations are needed. These are the laws of movement of motion of the resource at each border, evaluated at the steady state. They imply: $a^i = \bar{a}^i - \frac{1}{\delta} \cdot \left[\psi^{ii} \cdot \sum_f r_f^i \cdot x_f^i - \psi^{-ii} \cdot \sum_f r_f^{-i} \cdot x_f^{-i} \right]$ for i=1,2. Then, knowing the steady states for the a's and the p's, the steady states for all the other variables can be easily calculated using the corresponding formulas[21].

♦ *Compute the quadratic approximation of the objective function at the steady state*

For the case of a two variable objective function, the quadratic approximation around the steady state implies using the following Taylor's series expansion:

$$\begin{aligned} f(x,y) \cong\ & f(x,y) + f_x(x,y)\cdot(x-x) + f_y(x,y)\cdot(y-y) \\ & + \frac{1}{2}\cdot\left[f_{xx}(x,y)\cdot(x-x)^2 + 2\cdot f_{xy}(x,y)\cdot(x-x)\cdot(y-y) + f_{yy}(x,y)\cdot(y-y)^2 \right] \end{aligned}$$

where x and y are any variable. In this example there are much more variables. In the computer, this procedure uses approximated derivatives for all the variables of the problem so as to convert the objective function into a quadratic form $w' \cdot q \cdot w$, where w is a 17x1 vector of the state and decision variables in the problem (plus a constant) and q is a 17x17 matrix which contains the coefficients which approximate the objective function.

♦ *Solve for the value function of the Bellman's equation*

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[21] The resulting steady states are obtained using a non-linear simultaneous equation solving procedure in GAUSS. Different initial conditions always yield the same steady states, which shows that non-uniqueness is not a problem in this exercise.

After the quadratization of the objective function, the overall problem is now a linear-quadratic one, and can be written as: $V(a^1, a^2) = max\{w' \cdot q \cdot w + \beta \cdot V(a'^1, a'^2)\}$ $s.t.$ $z' \cdot C \cdot x$, where z is the vector of the state variables in t+1 and x is a 20x1 vector containing both w and z. Hence, the problem can be rewritten in a matrix form as: $V(a^1, a^2) = max\{x' \cdot R \cdot x\}$ $s.t.$ $z' \cdot C \cdot x$, where R is a 20x20 matrix of the form: $\begin{bmatrix} q & 0 \\ 0 & \beta \cdot V \end{bmatrix}$.

Given an arbitrary guess for V, the problem can be solved using a fixed-point argument of the form T(V)=V. More precisely, C is used to reduce 3 rows and 3 columns from R, and then the FOCs of the problem are used to reduce 14 more rows and columns[22]. The remaining matrix has only 3 rows and 3 columns, and gives an expression for TV. If such expression is different from V, then it is used as the new guess. After several iterations, the converged value function is obtained.

♦ *Compute the decision rules as functions of the state variables*

Knowing the value function, the policy functions can be derived from it because the rows of the R matrix correspond to the coefficients of the FOC of the Bellman's equation. In this problem, with 14 decision variables, the set of all rows is equivalent to a system of FOC from which the policy functions arise for all decision variables.

ii. Steps for the Simulation of Level II

No Environmental Regulation

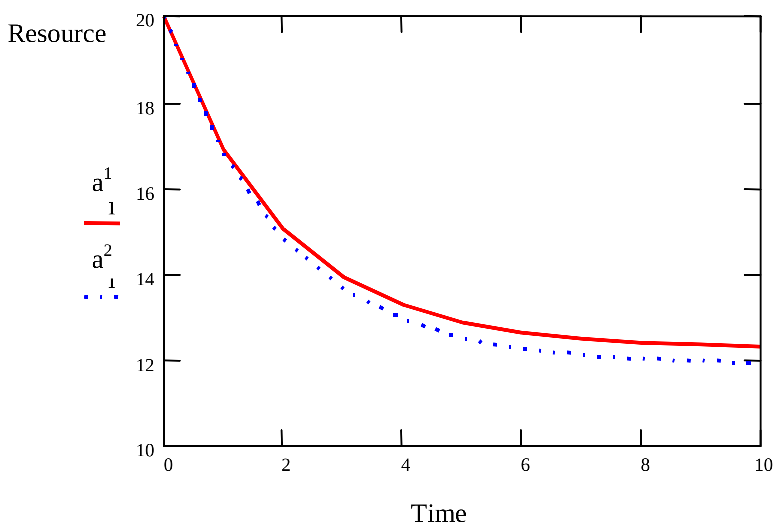
The equilibrium without any kind of environmental policy does not require much calculation, since the problems of consumers and producers are basically static. Each type of consumer in each country decides its demand for the commodity so as to equate price to marginal utility). Each type of firm chooses the supply of the commodity so as to equate price to marginal cost. Hence, the corresponding functions are: $c_h^i = \frac{A_h}{p^i}$ for i = 1, 2 and h =1, 2 , $y_f^i = \frac{p^i}{D_f}$ for i = 1, 2 and f = 1, 2. Emissions are proportional to production: $x_f^i = E_f \cdot y_f^i$ for i = 1, 2 and f = 1, 2.

In equilibrium, consumption has to be equal to production so that: $\sum_h s_h^i \cdot c_h^i = \sum_f r_f^i \cdot c_f^i$ for i=1,2. Prices in each country depend on tastes and production costs, and therefore: $\mathrm{p}^{\mathrm{i}} = \sqrt{\frac{\sum_{\mathrm{h}} \mathrm{s}_{\mathrm{h}}^{\mathrm{i}} \cdot \mathrm{A}_{\mathrm{h}}}{\sum_{\mathrm{f}} \frac{\mathrm{r}_{\mathrm{f}}^{\mathrm{i}}}{\mathrm{D}_{\mathrm{f}}}}}$ for i=1,2. As a result of these choices, the stock of the resource in each border changes according to the following equations: $a'^i = \overline{a^i} \cdot \delta + a^i \cdot (1-\delta) - \psi^{ii} \cdot \sum_f r_f^i \cdot x_f^i - \psi^{-ii} \cdot \sum_f r_f^{-i} \cdot x_f^{-i}$ for i=1,2.

[22] For the reduce procedure, the order of the variables is important because it consist basically in replacing one FOC into the other as a way to solve the problem. Then, Lagrange multipliers have to be placed before consumption, production and pollution because they are all function of prices.

Figure 2 depicts the movement of the resource over time beginning at its pristine state, in the case of a completely unregulated equilibrium. Clearly, country 1 (the "cleaner" country) always has its border in a better state than country 2.

Figure 2: Movement of the resource along time in absence of any regulation



The steady states for all the variables can be calculated directly by first substituting the parameters in the prices, and then, these in the demands and supplies. Finally, after plugging production into the FOC for emissions, the steady state for the resource results from its equation of motion.

ii. Domestic Environmental Policy

To analyze the case of both countries doing domestic environmental policy requires the solution of a more complicated problem: the simulation of a Markov-Perfect equilibrium. The government of each country decides on its domestic pollution taking the other country's actions as given, so in the problem of country 1, emissions by country 2 are not controls and viceversa. The steps to follow in this case are a variation of the method employed by Hansen and Prescott (1994) to compute recursive competitive equilibria[23].

♦ *Define the variables and the functions to maximize*

The number of decision variables is different from the one seen in section IV.1), because each country's problem is half the dimension of the supra-national planner. The number of state variables in each government problem is the same as in 1), because the intertemporal welfare in each country change when the other one takes less care of the resource. But, each of those problem has 9 additional variables (2 pollution variables from the other country, 2 own emissions, 1 price, 2 consumption and 2 productions).

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[23] There are some authors in the Industrial Organization literature who derived algorithms to compute Markov-Perfect equilibria of a multi-firms model (e.g., Pakes and McGuire, 1994). However, their techniques (using grids to derive non-linear policy functions) differ from those in this paper, even when the general idea of solving simultaneous dynamic programming problems is the same.

♦ *Define matrices for the laws of motion of the state variables*

In this case, two matrices C (3x15) have to be defined, one for each country. As before, the number of rows corresponds to one row for a constant term and two rows for the equation of motion of each of the resources. The number of columns is determined by a column for a constant, 2 columns for the state variables in period t, 2 columns for the other country emissions, 7 columns for the own decision variables and 3 more columns for the constant and the state variables in period t+1.

♦ *Compute the steady states for all the variables from the FOC*

As the objective functions are different, so are the FOC for pollution. The terms K^i are smaller because at level II only the harm from domestic firms to domestic consumers is internalized: $K^i = \frac{\beta}{1-\beta\cdot(1-\delta)}\cdot\left[\psi^{ii}\cdot\left(\sum_h \frac{s_h^i \cdot B_h}{a^i}\right)\right]$. Except for this, the way to solve for the steady states is the same than in level I.

♦ *Compute the quadratic approximation of the objective functions at the steady state*

The procedure used is the same one used for level I, except that the number of variables is smaller, and that there are two objective functions.

♦ *Solve for the value functions of the two Bellman's equations*

The way to solve for V^i is different because each country takes the pollution of the other as given, so both dynamic programming problems have to be solved simultaneously. The first step to solve together those two problems consists in replacing the 5 FOC for countries' own productions, consumptions and price. Then, comes the simultaneous part. The problem is that in country 1's problem there is no FOC to reduce pollution from country 2 because the former does not decide foreign emissions, and viceversa. So, while "reducing" the value function, the FOC for pollution of country 1 (which depends on pollution in country 2) is considered together with the FOC for country 2's pollution (which depends on country 1' s emissions).

The idea is that in equilibrium, countries have some expectations about the policy function of the other country. More precisely, the pairs of FOC of the two problems are used to express emissions as functions only of a^1 and a^2. Then, the corresponding results for emissions in country 2 are plugged into country 1's problem and the reverse happens with country 2. Finally, pollution FOC are reduced from the two problems, and the same procedure than in level I is used to get the value functions of each country as functions of the state variables.

♦ *Compute the decision rules as a function of the state variables*

Knowing the value functions, the policy functions can be derived from the respective FOC.

3) Results of the Simulation

The results of the simulation can be summarized by the steady states, the policy functions for pollution, and the resulting welfare, surpluses and prices.

i. The Steady States of all the Variables

Table 1 shows that the values of the steady states for all the variables in the case of some domestic policy are between those of the unregulated equilibrium and those of the overall optimum. The state of the resource is better if there is international cooperation than in the other two situations basically because the pollution allowed is much lower. The country which has the greater proportion of environmentally oriented consumers and cleaner firms also has the higher quality of the resource at the steady state in all circumstances.

There is a clear trade-off between production, consumption and a cleaner environment, since the former is lower at level I for both countries and for every type of firm and consumer. Within each country, consumers of type 1 (who care more about the resource) consume less than the other type. Moreover, firms produce the same in absence of any regulation, because they are equally efficient and their only difference is the extent to which their technology pollutes. However, once the government begins to regulate them, the "dirtier" firms produce less than the ones which use a cleaner technology, reflecting the achievement of the regulation's goal. This fact is reinforced when both countries sign an agreement to lower emissions (level I).

Table 1: Steady states of all the variables in the simulation

		Domestic level (II)		***International level (I)***
		Unregulated	***Regulated***	
Consumption	***country 1/type 1***	2.90474	2.74919	2.70516
	/type 2	3.55023	3.36012	3.30631
	country 2/type 1	2.79078	2.68414	2.58788
	/type 2	3.41096	3.28061	3.16297
Production	***country 1/type 1***	3.09839	2.98934	2.95908
	/type 2	3.09839	2.79978	2.71382
	country 2/type 1	3.22490	3.18165	3.14549
	/type 2	3.22490	3.06739	2.92399
Pollution	***country 1/type 1***	4.64758	2.58837	1.98599
	/type 2	7.74597	5.10380	4.33192
	country 2/type 1	4.83735	3.62992	2.50322
	/type 2	8.06226	6.52593	5.09496
Resource	***country 1***	12.26978	14.66418	15.82395
	country 2	11.89036	14.08565	15.41704

ii. The Policy Functions for Emissions[24]

Since the particular interest of this paper is to clarify the difference among different environmental regulatory situations, the focus has to be more on the policy functions for emissions rather than those for consumption and production (table 2). In an unregulated equilibrium, firms always pollute the same amount, but when the government of each country regulates, it does so according to

[24] The derived policy functions are linear and they are the result of quadratizing the objective function around the steady state. Hence, they are approximations of the real policy functions for the problem, but as such they provide a guide for the path of emissions.

the level of the resource. Therefore, it will establish taxes, quotas or permits to induce paths of emission, as reported in the second column of figure 2. These policy functions are the result of solving a system of 4 equations, because the policy function for each type of firm in each country depends on the other one (e.g., $x_1^1 = d(a^1, a^2, x_1^2, x_2^2)$, $x_1^2 = d_*(a^1, a^2, x_1^1, x_2^1)$, see definition 2).

Table 2: Emission functions at the two levels

	Domestic level (II)		International level (I)
	Unreg.	*Regulated.*	
country 1/type 1	4.64758	$1.85715 + .05078a^1 - .00095a^2$	$1.06205 + .04224a^1 + .01658a^2$
/type 2	7.74597	$4.15149 + .06612a^1 - .00123a^2$	$3.14834 + .05411a^1 + .02123a^2$
country 2/type 1	4.83735	$3.20993 - .00087a^1 + .03073a^2$	$1.69438 + .02660a^1 + .02516a^2$
/type 2	8.06226	$5.97985 - .00112a^1 + .03993a^2$	$4.06860 + .03376a^1 + .03192a^2$

Figure 3 shows the policy for pollution at level I (for firm of type 1 in country 1) as a function of *any* a_1 and a_2. Figure 4 shows that same situation when a_1 and a_2 follow their optimal paths because every type of firm in both countries follow the Markov-Perfect emission strategies (beginning at the level II unregulated state of the resource). From both pictures it is clear that when governments set an environmental policy, there is a "jump" down in the amount of the emissions allowed (for x^1_1, from 4.65 to 2.46), and as the resource improves, the regulation become slightly less tight (those emissions are allowed to increase up to 2.58). Moreover, if the neighbors do not take care of the resource, regulations have to be more stringent because the national government expects the other country to allow more pollution in the following periods. Hence, emissions depend on the resource at both borders.

If all externalities are internalized through an international agreement (like the one a supranational planner would propose), governments have to adopt a stricter regulation to match the optimal emissions which follow the policy functions derived for level I. The resulting policy function for emissions is shown at figure 5 (for firm type 1 in country 1). In the first period of the agreement, countries should commit to a decrease in their emissions by firms of type 1 of 25% (from 2.58 to 1.92) and 32% (from 3.62 to 2.44) for country 1 and 2 respectively, if they previously had their domestically optimum pollution policies in place. Note also that in this case, pollution levels depend positively on the two levels of the resource, because coordination makes each country treat the other's resource in the same way as its own.

Figure 3: Domestically Efficient Pollution Policy

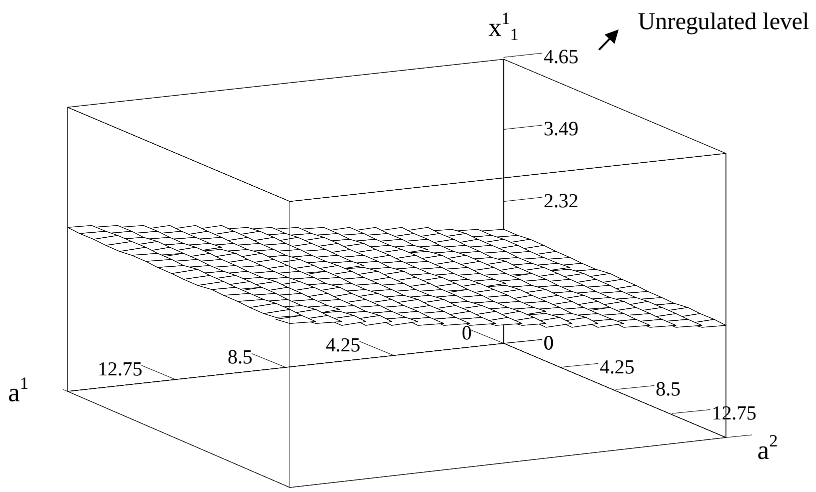


Figure 4: Domestically Efficient Pollution Policy followed by both countries

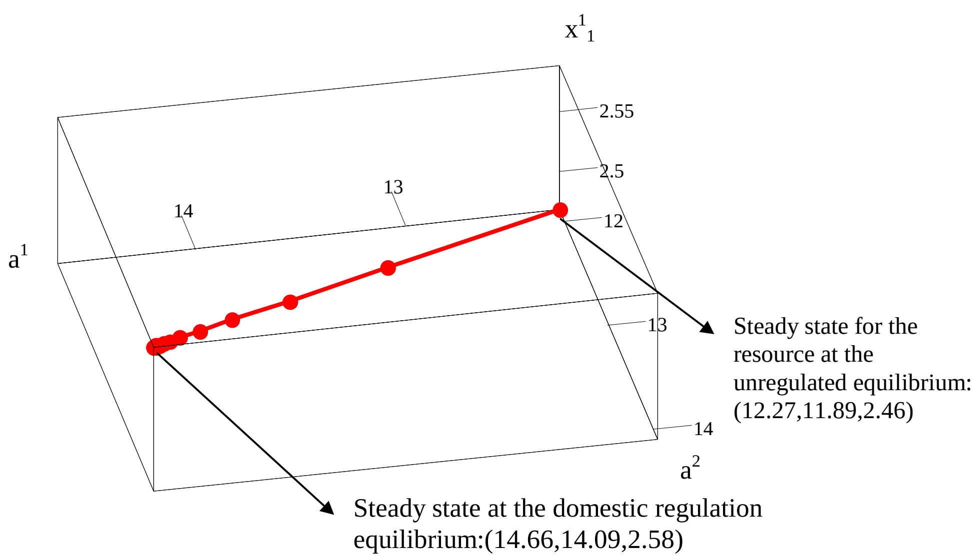
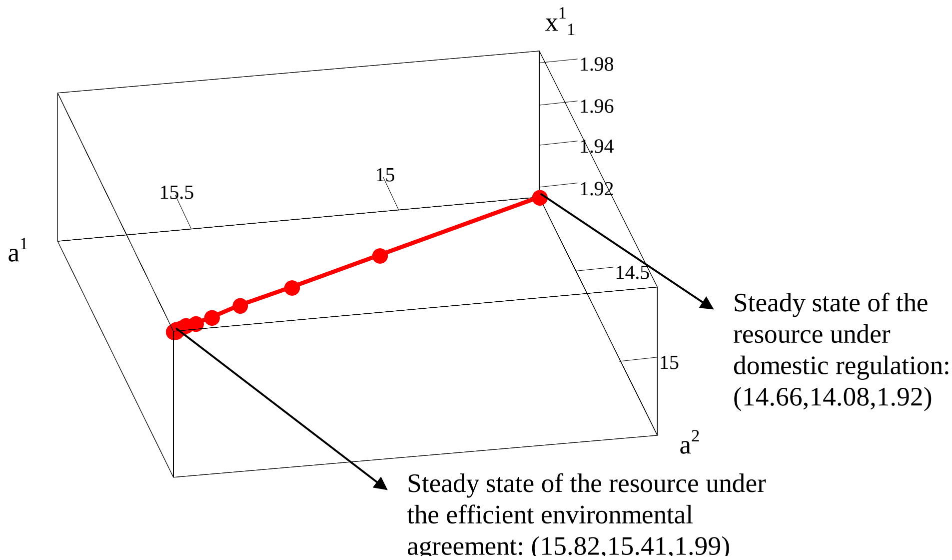


Figure 5: Fully efficient policy followed by both countries



iii. Resulting Gains, Surpluses and (Implicit) Prices

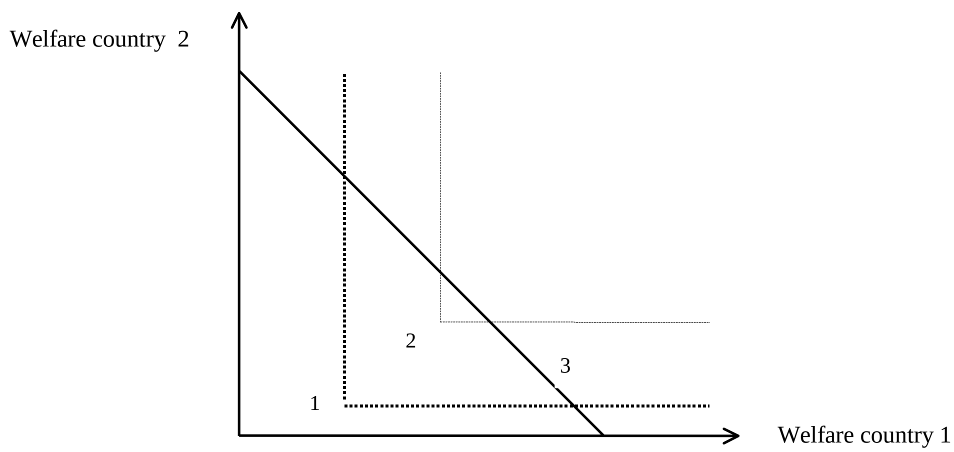
The welfare (the surpluses for the firms and consumers in each country) are compared at the steady state in table 3. In both countries, consumers and firms of type 1 (more worried about the environment) benefit from any sort of environmental regulation.

Table 3: Gains, surpluses and (implicit) prices at the two levels

	Domestic level (II)		***International***
	Unregulated	***Regulated***	***level (I)***
Country 1	156.26237	160.92172	162.39401
Consumer 1	131.32786	135.28807	137.64071
Consumer 2	54.44291	50.17167	49.15671
Firm 1	126.15536	131.12020	132.34926
Firm 2	49.72644	47.13490	44.02091
Country 2	124.65512	127.56227	127.30102
Consumer 1	42.00000	51.38417	51.65943
Consumer 2	62.00000	50.66548	50.45635
Firm 1	38.00000	55.41454	57.46849
Firm 2	58.00000	55.15346	56.48723
Both countries	280.91749	288.48399	289.69503
Price country 1	30.98387	32.73688	33.26976
Price country 2	32.24903	33.53032	34.77747

In general, consumers and firms of type 2 are worse off with regulations due to the impact that those have on prices, production and consumption. Not only does the level I result in a better state of the resource but also in a higher overall surplus, because it reflects an efficient situation. The differences in welfare are not too large due to the values of the parameters chosen, but the fact that the problem is not symmetric creates a particularity in the space of payoffs: country 2 is better off doing only domestic policy (at the same time that country 1 also does that) than going to a stage of international cooperation. Hence, any such agreement must be accompanied by money transfers from country the "cleaner" country to the "dirtier" country, in order to induce the latter to change its environmental policy (figure 6).

Figure 6: Welfare for both countries at the two levels (asymmetric case)



Prices also change according to each level in a consistent way, in the sense that they are higher at level I, lower at the regulated level II, and even lower at the unregulated level II. Prices are also lower in the country in which consumers are more environmentally oriented and firms are cleaner.

V. Summary and Conclusions

This paper provides a deeper analysis of international negotiations than other models in the literature of dynamic games applied to environmental economics, since countries are modeled as spaces that also contain consumers and firms. Moreover, it goes a step further by considering that governments may already be engaged in domestic environmental regulation.

The model delineates some possible circumstances in which an international environmental negotiation may begin. It may be that all countries involved are doing domestic environmental policy, and so they tighten their regulation in order to take into account the harm that they impose on each other. It may also happen that only some countries are previously engaged in some environmental policy, or that none of them have actual policies in effect. The occurrence of each of these cases (together with consumers' and firms' characteristics in each country) limits the range of agreements' possibilities among countries. In addition, the framework utilized is helpful to conceptualize the need for transfers in some circumstances (for example when one of the countries has consumers and firms which are more environmentally oriented than the other, and so is clearly willing to compensate the other country if it reduces its emissions). The numerical simulation for a renewable resource in a linear-quadratic framework allows the derivation of approximate policy trajectories for each firm and aggregate pollution which result from different equilibria, as well as intertemporal surpluses under the different circumstances depend on the state of the resource.

Further research can enrich this model by incorporating additional features: a more complete framework which includes information problems and political pressure (both at the national and the international levels) while preserving the dynamics, considerations of implementation costs, calibration of the model using parameters derived from an empirical study of a concrete case, or a more explicit modeling of transfers.

Appendix A: Computer Program for the Numerical Simulation of level II

```
new;
library nlsys,pgraph,user;
output file=c:\gauss\disser1.out reset;
format 9,5;

@ INFORMATION NECESSARY FOR THE SIMULATION@

@ Dimensions of the problem @
        np=2;                                   @number of countries sharing the resource@
        nc=2;                                   @number of types of consumers in each country@
        nf=2;                                   @number of types of firms in each country@
@ Functional forms:  vih=[Ah*log cih+Bh*log ai]  and TCif=(Df/2)*cif^2-(1/2)*(Ef*cif-xif)^2@
@ Parameter Values @
        psi=zeros(np,np);                                   @transport matrix@
        psi[1,1]=.3;psi[2,2]=.3;                            @effect of own country pollution@
        psi[1,2]=.2;psi[2,1]=.2;                            @effect of other country pollution@
        pva=zeros(nc,1);pva[1:nc,1]=seqa(90,20,nc);         @A for all consumers@
        pvb=zeros(nc,1);pvb[1:nc,1]=seqa(50,-40,nc);        @B for each type of consumers@
        pvd=zeros(nf,1);pvd[1:nf,1]=1./seqa(10,0,nf);       @1/D for each type of firms@
        pve=zeros(nf,1);pve[1:nf,1]=seqa(1.5,1,nf);         @E for each type of firms@
        massc=zeros(nc,nc);
        massc[1,1]=.7;massc[2,2]=.7;                        @% people of each type in each country@
        massc[1,2]=.3;massc[2,1]=.3;
        massf=zeros(nf,nf);
        massf[1,1]=.7;massf[2,2]=.7;                        @% firms of each type in each country@
        massf[1,2]=.3;massf[2,1]=.3;
        beta=.99;
        delta=.4;                                           @natural decay of pollutants@
        abar=20;                                            @pristine state of the resource@

@ Define the variables and the functions to maximize@
        nss=3;                      @(1,a are the states,then the decision of the other country xj)@
        ndd=7;                      @c for each type,y for each type,x for each type,p1@
@  The variables form the vectors t1 and t2:  t1[1,1]=a1; t1[2,1]=a2; t1[3,1]=x21; t1[4,1]=x22; t1[5,1]=x11; t1[6,1]=x12;
t1[7,1]=p1; t1[8,1]=c11; t1[9,1]=c12; t1[10,1]=y11; t1[11,1]=y12; t2[1,1]=a1; t2[2,1]=a2; t2[3,1]=x11; t2[4,1]=x12;
t2[5,1]=x21; t2[6,1]=x22;  t2[7,1]=p2;     t2[8,1]=c21; t2[9,1]=c22; t2[10,1]=y21; t2[11,1]=y22@
        proc retf1(t1);
        local c1,c3,c31,r1,r3,rr;
        c1=ln(t1[8,1]|t1[9,1]);
        r1=massc[.,1].*(pva.*c1+pvb*ln(t1[1,1])-t1[7,1]*(t1[8,1]|t1[9,1]));
        c3=(t1[10,1]|t1[11,1]); c31=(t1[5,1]|t1[6,1]);
        r3=massf[.,1].*(t1[7,1]*c3-(.5/pvd).*(c3^2)-(.5)*((pve.*c3-c31)^2));
        rr=r1[1,1]+r1[2,1]+r3[1,1]+r3[2,1];
        retp(rr);
        endp;
        proc retf2(t2);
        local c2,c4,c41,r2,r4,rrr;
        c2=ln(t2[8,1]|t2[9,1]);
        r2=massc[.,2].*(pva.*c2+pvb*ln(t2[2,1])-t2[7,1]*(t2[8,1]|t2[9,1]));
        c4=(t2[10,1]|t2[11,1]); c41=(t2[5,1]|t2[6,1]);
        r4=massf[.,2].*(t2[7,1]*c4-(.5/pvd).*(c4^2)-(.5)*((pve.*c4-c41)^2));
        rrr=r2[1,1]+r2[2,1]+r4[1,1]+r4[2,1];
        retp(rrr);
        endp;
```

@Define matrices for the laws of motion of the state variables@

```
cc1=zeros(nss,2*nss+ndd+2); cc2=zeros(nss,2*nss+ndd+2);          @add 1 for xj@
cc1[1,1]=1;cc1[2,1]=abar*delta;cc1[2,2]=(1-delta);
cc1[2,4]=-psi[2,1]*massf[2,1];cc1[2,5]=-psi[2,1]*massf[2,2];
cc1[2,6]=-psi[1,1]*massf[1,1];cc1[2,7]=-psi[1,1]*massf[1,2];
cc1[3,1]=abar*delta;cc1[3,3]=(1-delta);
cc1[3,4]=-psi[2,2]*massf[2,1];cc1[3,5]=-psi[2,2]*massf[2,2];
cc1[3,6]=-psi[1,2]*massf[1,1];cc1[3,7]=-psi[1,2]*massf[1,2];
cc2[1,1]=1;cc2[2,1]=abar*delta;cc2[2,2]=(1-delta);
cc2[2,6]=-psi[2,1]*massf[2,1];cc2[2,7]=-psi[2,1]*massf[2,2];
cc2[2,4]=-psi[1,1]*massf[1,1];cc2[2,5]=-psi[1,1]*massf[1,2];
cc2[3,1]=abar*delta;cc2[3,3]=(1-delta);
cc2[3,6]=-psi[2,2]*massf[2,1];cc2[3,7]=-psi[2,2]*massf[2,2];
cc2[3,4]=-psi[1,2]*massf[1,1];cc2[3,5]=-psi[1,2]*massf[1,2];
```

@ Compute the variables' steady state @

```
t1s=zeros(nss+ndd+1,1); t2s=zeros(nss+ndd+1,1);
proc resol1(m1);
local b,K1,K2,p1,p2,y1,y2,x1,x2,xx,xxa,xxa1,xxa2,xx1,xx2,l,eqns1;
b=beta/(1-beta*(1-delta));
K1=b*((psi[1,1]*massc[.,1]'*pvb)/m1[1,1]);K2=b*((psi[2,2]*massc[.,2]'*pvb)/m1[2,1]);
y1=(m1[3,1]*pvd)-(pvd.*pve*K1);          @production both types of firms country 1@
y2=(m1[4,1]*pvd)-(pvd.*pve*K2);          @production both types of firms country 2@
x1=(pve.*y1)-K1; x2=(pve.*y2)-K2;
xx=x1~x2;xxa=massf.*xx; xxa1=xxa*psi[.,1]; xxa2=xxa*psi[.,2];
xx1=xxa1[1,.]+xxa1[2,.]; xx2=xxa2[1,.]+xxa2[2,.];
eqns1=zeros(4,1);
eqns1[1,1]=m1[1,1]*delta-abar*delta+xx1;eqns1[2,1]=m1[2,1]*delta-abar*delta+xx2;
eqns1[3,1]=(m1[3,1]^2)*massf[.,1]'*pvd-m1[3,1]*(massf[.,1]'*(pve.*pvd*k1))-massc[.,1]'*pva;
eqns1[4,1]=(m1[4,1]^2)*massf[.,2]'*pvd-m1[4,1]*(massf[.,2]'*(pve.*pvd*k2))-massc[.,2]'*pva;
retp(eqns1);
endp;
{ts,ttf,ttj,ttrc}=nlsys(&resol1,15|15|30|30);if ttrc>1; "Return code is";;ttrc;;endif;

t1s[1,1]=ts[1,1]; t2s[1,1]=t1s[1,1];                 @a1@
t1s[2,1]=ts[2,1]; t2s[2,1]=ts[2,1];                  @a2@
b=beta/(1-beta*(1-delta));
K1s=b*((psi[1,1]*massc[.,1]'*pvb)/ts[1,1]);K2s=b*((psi[2,2]*massc[.,2]'*pvb)/ts[2,1]);
t1s[7,1]=ts[3,1];  @p1@          t2s[7,1]=ts[4,1];  @p2@
c1s=pva./t1s[7,1]; c2s=pva./t2s[7,1];
y1s=(t1s[7,1]*pvd)-(pve*K1s.*pvd); y2s=(t2s[7,1]*pvd)-(pve*K2s.*pvd);
x1s=(pve.*y1s)-K1s; x2s=(pve.*y2s)-K2s;
t1s[8,1]=c1s[1,1];t1s[9,1]=c1s[2,1];t2s[8,1]=c2s[1,1];t2s[9,1]=c2s[2,1];          @consumption ss@
t1s[10,1]=y1s[1,1];t1s[11,1]=y1s[2,1];t2s[10,1]=y2s[1,1];t2s[11,1]=y2s[2,1];      @production ss@
t1s[5,1]=x1s[1,1];t2s[3,1]=x1s[1,1];t1s[6,1]=x1s[2,1];t2s[4,1]=x1s[2,1];          @pollution ss@
t1s[3,1]=x2s[1,1];t2s[5,1]=x2s[1,1];t1s[4,1]=x2s[2,1];t2s[6,1]=x2s[2,1];
ssIIR1=t1s;ssIIR2=t2s;
```

@ Compute the quadratic approximations of return functions @

```
q1=quad(t1s,0.000001,&retf1);q2=quad(t2s,0.000001,&retf2);
```

@ Solve for the value functions of the simultaneous Bellman's equations @

```
test1=10;test2=10;
nn=nss+ndd;
v1=eye(nss)*(-.0001); format /rd 8,5;v2=eye(nss)*(-.0001); format /rd 8,5;
iter1=0;
do until test1 lt 1E-10 or test2 lt 1E-10 or iter1>1000;
```

```
tv1=q1~zeros(nn+2,nss)|zeros(nss,nn+2)~(v1*beta);tv2=q2~zeros(nn+2,nss)|zeros(nss,nn+2)~(v2*beta);
nvv1=rows(tv1);  nvv2=rows(tv2);
if iter1<1;format 9,3;"original full tv1";tv1;endif;if iter1<1;format 9,3;"original ful tv2";tv2;endif;

@Reduce out laws of motion for state variable.@
        i=1;
        do until i>nss;
        tv1=reduce(tv1,cc1[nss-i+1,1:nvv1-i]); tv2=reduce(tv2,cc2[nss-i+1,1:nvv2-i]);
        i=i+1;
        endo;
        if iter1<1;format 9,3;"partial tv1 after reduce law of motions of a";tv1;endif;
        if iter1<1;format 9,3;"partial tv2 after reduce law of motions of a";tv2;endif;

  @Reduce out first order conditions for consumption and production@
        dsave1=tv1[nss+3:nn+2,1:nn+2];dsave2=tv2[nss+3:nn+2,1:nn+2];
        i=1;
        do until i>5;
        d1=-tv1[nn-i+3,1:nn-i+2]./tv1[nn-i+3,nn-i+3]; tv1=reduce(tv1,d1);
        i=i+1;
        endo;
        i=1;
        do until i>5;
        d2=-tv2[nn-i+3,1:nn-i+2]./tv2[nn-i+3,nn-i+3]; tv2=reduce(tv2,d2);
        i=i+1;
        endo;
        if iter1<1;format 9,3;"partial tv1 after reduce FOC of c and y";tv1;endif;
        if iter1<1;format 9,3;"partial tv2 after reduce FOC of c and y";tv2;endif;
        @Solve x11,x12,x21,x22 as fn of a1 and a2 in order to be able to reduce both variables for which one of
        the countries has no FOC because no control on them@
        sis=zeros(4,7);sis[1,.]=tv1[6,.];sis[2,.]=tv1[7,.];sis[3,.]=tv2[6,.];sis[4,.]=tv2[7,.];
        @rearranging because diff order x var@
        auxi=zeros(2,2);auxi[1:2,1:2]=sis[1:2,4:5];
        sis[1:2,4:5]=sis[1:2,6:7];sis[1:2,6:7]=auxi[1:2,1:2];
        if iter<1;format 9,5;print sis;endif;
        siss=-sis[.,1:3]/sis[.,4:7];msave=siss[.,.];
        if iter1<1;format 9,5;"solving x1 and x2 as function of a (iter1)";;siss;endif;
        tv1[4,4]=-1;tv1[4,5:7]=zeros(1,3);tv1[5,4:7]=zeros(1,4);
        tv1[5,5]=-1;tv2[4,4]=-1;tv2[4,5:7]=zeros(1,3);tv2[5,4:7]=zeros(1,4);
        tv2[5,5]=-1;tv1[4:5,1:3]=siss[3:4,.];tv2[4:5,1:3]=siss[1:2,.];
        if iter1<1;format 9,3;"partial tv1 before reduce x1 and x2 cont";tv1;endif;
        if iter1<1;format 9,3;"partial tv2 before reduce x1 and x2 cont";tv2;endif;

@Reduce the controlled x's as usual FOC@
        i=1;
        do until i>2;
        d11=-tv1[ndd-i+1,1:ndd-i]./tv1[ndd-i+1,ndd-i+1]; tv1=reduce(tv1,d11);
        i=i+1;
        endo;
        i=1;
        do until i>2;
        d21=-tv2[ndd-i+1,1:ndd-i]./tv2[ndd-i+1,ndd-i+1];
        tv2=reduce(tv2,d21);
        i=i+1;
        endo;
        if iter1<1;format 9,3;"partial tv1 before reduce x1 and x2 uncont";tv1;endif;
        if iter1<1;format 9,3;"partial tv2 before reduce x1 and x2 uncont";tv2;endif;
```

```
@Reduce the uncontrolled x's @
        i=1;
        do until i>2;
        d12=-tv1[ndd-2-i+1,1:ndd-2-i]./tv1[ndd-2-i+1,ndd-2-i+1];
        d22=-tv2[ndd-2-i+1,1:ndd-2-i]./tv2[ndd-2-i+1,ndd-2-i+1];
        tv1=reduce(tv1,d12); tv2=reduce(tv2,d22);
        i=i+1;
        endo;
        if iter1<1;format 9,3;"partial tv1 before reduce x1 and x2 cont";tv1;endif;
        if iter1<1;format 9,3;"partial tv2 before reduce x1 and x2 cont";tv2;endif;
test1=abs(tv1-v1); test1[1,1]=0;test2=abs(tv2-v2); test2[1,1]=0;
v1=tv1;v2=tv2;
iter1=iter1+1;
endo;
```

@ Compute the decision rules as functions of the state variables @

```
decis1=-dsave1[.,1:nss+2]/dsave1[.,nss+3:nn+2];
decis2=-dsave2[.,1:nss+2]/dsave2[.,nss+3:nn+2];
```

@Check: Auxiliary calculations for pollution policy functions@

```
car=zeros(4,7);car[1:2,1:3]=decis1[1:2,1:3];car[1:2,6:7]=decis1[1:2,4:5];car[3:4,1:5]=decis2[1:2,.];
aux=car[.,1:3]/(eye(4)-car[.,4:7]);
print "Policy fn of pollution (at the end)"; aux;
print "Policy fn of pollution (intermediate)";siss;

@ Compute steady states from decision rules and compare with original steady states (use law of motion for a)@
proc ger(fp);
local mam1,mam2,mam,mama,mama1,mama2,pa1,pa2,eqnsf;
mam1=decis1[1:2,.]*(1|fp[1,1]|fp[2,1]|fp[5,1]|fp[6,1]);
mam2=decis2[1:2,.]*(1|fp[1,1]|fp[2,1]|fp[3,1]|fp[4,1]);
mam=mam1~mam2;mama=massf.*mam;mama1=mama*psi[.,1];mama2=mama*psi[.,2];
pa1=mama1[1,.]+mama1[2,.];pa2=mama2[1,.]+mama2[2,.];
eqnsf=zeros(6,1);
eqnsf[1,1]=fp[1,1]*delta-abar*delta+pa1;eqnsf[2,1]=fp[2,1]*delta-abar*delta+pa2;
eqnsf[3,1]=fp[3,1]-decis1[1,.]*(1|fp[1,1]|fp[2,1]|fp[5,1]|fp[6,1]);
eqnsf[4,1]=fp[4,1]-decis1[2,.]*(1|fp[1,1]|fp[2,1]|fp[5,1]|fp[6,1]);
eqnsf[5,1]=fp[5,1]-decis2[1,.]*(1|fp[1,1]|fp[2,1]|fp[3,1]|fp[4,1]);
eqnsf[6,1]=fp[6,1]-decis2[2,.]*(1|fp[1,1]|fp[2,1]|fp[3,1]|fp[4,1]);
retp(eqnsf);
endp;
{fpp,ttf,ttj,ttrc}=nlsys(&ger,19|19|2|2|2|2); if ttrc>1; "Return code is";;ttrc;;endif;
```

Appendix B: Derivation of the Resource Constraint Used in the Simulation

The depletion of the resource occurs trough pollution. Considering the resource is at its natural stage ($\bar{a}$), pollution (p) harms it in the following way:

$$a = \bar{a} - p$$

Then, pollution is naturally absorbed by the resource:

$$p' = (1-\delta) \cdot p$$

where 0<δ<1 is the rate of natural cleaning of the resource, and p and p' are the pollution levels at t and t+1 respectively. The same equation can be rewritten as a function of time ($p = (1-\delta)^t \cdot p_o$), so the first equation can be expressed as

$$a = \bar{a} - \frac{p'}{1-\delta} \qquad \text{or} \qquad a = \bar{a} - \frac{a - a'}{1-\delta}$$

After some algebraic operations, this becomes:

$$a' = \bar{a} - (1-\delta) \cdot (\bar{a} - a) \qquad \text{or} \qquad a' = \bar{a} \cdot \delta + (1-\delta) \cdot a$$

which is the law of motion for the resource used in the simulation.

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