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Domestic environmental policy and international cooperation for global commons

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Abstract

The paper analyzes the strategic behavior of several countries engaged in capital accumulation, pollution mitigation, and environmental adaptation in the context of an environmental common good. Both cooperative and non-cooperative strategies are discussed. The non-cooperative strategy is a dynamic game in which each country makes its own environmental decision following the open-loop Nash equilibrium. The cooperative social planner problem assumes an international environmental agreement in force. The non-cooperative and cooperative solutions are compared in the symmetric case of two countries and extended to several identical countries. It is shown that the non- cooperative strategy in multi-country world leads to over-production, over-consumption, over-pollution, and over-adaptation.

Keywords: climate policy, adaptation, mitigation, dynamic general equilibrium.

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1. Introduction

It is well recognized in the economic literature that global environmental problems require a global solution, that is, cooperation among the involved countries. It is also established that the absence of cooperation leads to the under-provision of pollution mitigation compared to the level optimal from a global standpoint. Countries interested in their own welfare tend to spend less on pollution mitigation. Because mitigating a global pollutant means contributing to a public good, it cannot be globally optimal without some coordination among countries. However, a country's environmental policy facing a global pollutant is not limited to mitigation. Recently, a new policy instrument appeared in the policy debate, namely, the environmental adaptation. In short, the adaptation consists in protecting a country from the adverse effects of pollution. When a country is unable to effectively control pollutions, for example, because of the lack of international cooperation, then adaptation is an open option of domestic policy that may be effective. Instead of spending money in vein on mitigation, the country may have an interest in spending on adaptation. The striking difference between mitigation and adaptation is that the former contributes to a public good while the latter is led by pure selfishness, to be understood here as the country's self interest. The intuition thus suggests that the lack of cooperation should lead to too little mitigation and too much adaptation. To justify this intuition, we must understand a country' motive to invest in mitigation and adaptation in a multi-country setting, that is, understand how optimal domestic policies are shaped by international cooperation.

The emerging literature on the optimal policy mix between mitigation and adaptation usually considers the adaptation as a spare wheel when mitigation fails. In this paper we question this statement. We will show that a much wider picture should be discussed when comparing domestic environmental policies under international cooperation and no-cooperation. This issue is of a major importance in designing effective environmental policies, and a key policy message of this paper is that the debates about international agreements and domestic policies should not be considered as separate issues.

During the last years, the literature devoted to managing global commons used to start from the top-level design of an international agreement and then scaled down to the nation level to find a domestic policy compatible with the international agreement, notably in terms of incentives (is the country willing to join the agreement?). Empirical evidence suggests that such an approach is ineffective. On one hand, the climate change multilateral negotiation process undergone on behalf of the United Nations Framework on Climate Change (UNFCCC) has failed to deliver concrete outcomes for many years.[1] On the other hand, despite the slow pace of the UNFCCC process, several domestic initiatives (at the national or sub-national levels) have been recently documented. A remarkable example is the GLOBE International initiative. GLOBE International was originally founded in 1989 by legislators from the US Congress, European Parliament, Japanese Diet and the Russian State Duma with the mission to respond to urgent environmental challenges through the development and advancement of national

[1]Let us wait for Paris COP conference in 2015 to be conclusive.

legislation.[2] Fankhauser *et al.* (2014) have recently analyzed national and international factors that drive the adoption of legislation on climate change with a unique dataset of 419 national legislation pieces from 63 countries. They showed that the passage to climate legislation is influenced by both domestic and international factors. This new perspective suggests that a positive policy context at the local level may eventually scale up at the global level and help an international agreement to come out. Their main conclusion warns against focusing too narrowly on international treaties as the sole solution to the climate problem, while domestic actions might be a possible route to unlock the stalemate in international negotiations. Indeed, strong interactions exist between the top and bottom parts when it comes to managing global commons.

A recent interesting theoretic tentative to bridge this top-down gap was proposed by Olstrom (2012) under the collective bi-disciplinary (economics and political sciences) research project initiated by Brousseau *et al*. (2012). Actually, a new strand of thinking is emerging that attempts to circumvent well-known drawbacks of the common top-down approach. A necessary ingredient for its success is better understanding how international agreements shape domestic policies, which is the purpose of our paper.

As it will be shown in the literature review (Section 2), the current research provides only partial answers to these questions. In this paper, we propose a comprehensive analysis of the key ingredients for economic growth and environmental policy in a multi-country dynamic general equilibrium setting. We consider the main drivers of economic growth, namely, investment in physical capital, investment in environmental adaptation, and spending on pollution mitigation. Our main findings can be summarized as follows.

We will first consider the simple case of a single country with the rest-of-the-world represented by a given exogenous external pollution stock. This setting will actually allow us to understand the effects related to the asymmetry among countries. The optimal adaptation policy depends on a combination of three factors, each of them having a strong economic rationale. First, the physical-technological potential for adaptation must be large enough, which is related to the country's geographical and physical characteristics. A country located is an area highly sensitive to global warming will probably have a wider technological potential than other countries. Second, the opportunity cost and incentive to invest in pollution abatement increase with the country's pollution level. The first two factors suggest that mitigation and adaptation may well be either substitutable or complementary policy instruments depending on the economy under analysis. Third, the wealth of the economy also plays a key role: a wealthier economy may have a stronger incentive to invest in adaptation than in mitigation, and it is optimal not to invest in adaptation if the economy is too poor. When discussing these factors, we will introduce a synthetic indicator of *country's environmental harm and vulnerability*, both for mathematical and economic purposes. It will prove to be an appealing indicator for policy support.

[2] The main publication is the GLOBE Climate Legislation Study (fourth edition). The Study is produced in partnership with the Grantham Institute at the London School of Economics and serves to baseline existing climate laws and regulation. It has been widely recognized for highlighting the growing trend of national climate change legislation. See: http://globelegislators.org.

This one-country setting allows us to analyze how the size of the economy influences its domestic policy. We show that the larger contribution of an economy to the global pollution stock leads to larger output, capital stock, and mitigation spending. Furthermore, a stronger environmental harmfulness reinforces this relationship. Optimal adaptation decisions are more challenging to understand. The optimal adaptation spending depends on both the harmfulness of the economy and its size. If the harmfulness is high, then optimal adaptation first increases and later decreases with the size of the economy. This is an important counter-intuitive result that would require to be empirically documented. It reveals that adaptation is not driven by selfishness only.

Then we consider a multi-country model. For the sake of clarity we will start with two countries before generalizing to n countries, $n > 2$. Indeed, all the results displayed for two countries will hold for n countries. We restrict the analysis to symmetric countries in steady state. In such a setting, two polar scenarios can be considered, namely non-cooperative and cooperative. The former corresponds to Nash equilibrium, the latter to a first-best Pareto solution. Comparing these two scenarios leads to a natural result, that the global pollution level is too high in the non-cooperative scenario with respect to the first best. Still, the reasons why it happens are not trivial. The first unexpected result (never mentioned in the literature to the best of our knowledge) is that the size of the economies significantly differs in the above two scenarios. The optimal size of the economy at steady state is always larger in the non-cooperative scenario than under cooperation. The lack of cooperation in the global pollution problem yields too fat economies, where not only pollution is too high, but also output, capital and consumption. Because countries cannot effectively control the global pollution level in the Nash scenario, they have no choice but to spend more on mitigation and adaptation, and because they need income for this purpose, more production and capital accumulation are required. We show that, expressed in terms of output, mitigation efforts are indeed too small in Nash scenario as it is well known in the literature, but mitigation expenses are larger compared to what they could be under cooperation because the whole economy is too fat. This is a wasteful economy where people work hard to get income to be able to spend a lot of money to cope with pollution. We also show that this wastefulness increases with the degree of environmental harmfulness.

The optimal policy ratio between adaptation and mitigation displays an inverse U-shape with respect to the stage of development of the economy (represented by its total factor productivity), as in Bréchet *et al.* (2013). In other words, mitigation and adaptation are complementary policy instruments for poor countries but become substitutes at some higher stage of development. A new result is that cooperation moves this inverse U-shape to the left. As a consequence, optimal adaptation becomes positive for smaller values of the total productivity in Nash than under cooperation, and the maximum of the optimal ratio between adaptation and mitigation is reached at a smaller total productivity value. This result has major implications for the current policy debate. It shows that the lack of cooperation does not necessarily lead to too much adaptation, but rather to too little adaptation in poor countries. It suggests that more should be spent in international adaptation funds to help developing countries in the absence of effective cooperation, which is a sensitive policy issue in the current international negotiation process.

The remainder of the paper is organized as follows. Section 2 provides a literature review. Section 3 introduces the model of a single country in a global environment, *i.e.,* with a given exogenous pollution flow coming from the rest of the world. This preliminary setting will conveniently allow us to show how asymmetry among countries shapes domestic policies. We will prove the existence and uniqueness of a steady state and produce qualitative results about optimal mitigation and adaptation policies. In this section, we will also obtain approximate analytic formulas necessary for further analysis of a multi-country world. Section 4 investigates the case of several countries. For the sake of clarity, we will start with a competitive two-country world (Section 4.1), *i.e.* a dynamic game in which each country makes its own environmental decision following the open-loop Nash equilibrium. A social planner problem, where decisions are taken by an international governmental body on the behalf of all countries, is described in Section 4.2. The choice of the Nash open-loop over feedback strategy and the comparison of Nash and cooperative scenarios are discussed in Section 4.3. Section 4.4 provides a generalization of major outcomes to $n > 2$ countries. Section 5 concludes.

2. Literature review

The current literature provides only partial insights to the question of the connection between domestic policies and international cooperation for a global common. It is mostly restricted to the applied integrated assessment modeling frameworks proposed by de Bruin *et al.* (2009a), de Bruin *et al*. (2009b), Bosello (2008), Bosello *et al.* (2010). A more theoretic strand is represented by Tulkens and van Steenberghe (2009), Buob and Stephan (2011) and Ebert and Welsch (2012). Let us review the main contributions of the aforementioned papers.

De Bruin *et al.* (2009a) and de Bruin *et al*. (2009b) consider aggregate adaptation expenditures as an endogenous flow variable in the numerical DICE model. They obtain that adaptation and mitigation are complementary policy instruments, adaptation is stronger in the short run, mitigation stronger in the long run, and adaptation is better for low environmental damages. Bosello (2008) considers aggregate adaptation expenditures as an endogenous stock variable of the RICE model and argues that the optimal mitigation starts earlier, adaptation is postponed, and mitigation is better for low damages. The later work of Bosello *et al.* (2010) distinguishes between three adaptation categories and mitigation in the AD-WITCH optimal growth model of the 12-region world. All these papers focus on computational models rather than providing theoretical insights.

The first theoretic paper related to our research is Tulkens and van Steenberghe (2009). They extend the standard cost minimization model (called “c+d” for abatement costs and damage costs minimization) by including adaptation costs explicitly in the damage function. They characterize the optimal (cost minimizing) balance between policy options (abatement, adaptation, and suffering) in both static and dynamic settings. Tulkens and van Steenberghe show that, in the cooperative solution, the optimal adaptation level at any time t is such that its marginal cost is equal to the discounted value of future suffered damages that adaptation allows to avoid. This suggests how adaptation and mitigation ought, in their view, to complement each other.

Two other analytic papers, Buob and Stephan (2011) and Ebert and Welsch (2012), use game-theoretic framework to analyze adaptation and mitigation in a multi-country setting. Buob and Stephan (2011) study a two-stage dynamic game of several identical regions with cooperative and non-cooperative behavior. They focus on the fundamental difference that adaptation benefits are private to a region while mitigation benefits are globally public. Some of their major qualitative conclusions are that poor countries should invest only in mitigation while rich countries should invest in both mitigation and adaptation. Thus, these countries provide public benefits of mitigation even in the case of non-cooperative behavior. Furthermore, the range of income for which the countries engage in adaptation is smaller under cooperation than under no-cooperation. Our analysis confirms and extends the results of Buob and Stephan (2011). Such coincidence is surprising given the differences between the modeling approaches. Ebert and Welsch (2012) consider a two-country static game with endogenous production, pollution emissions, and adaptation expenditures, but they do not explicitly model mitigation expenditures. They come to a related conclusion that a larger productivity of emissions and larger adaptive capacity lead to greater emissions, in the home country and globally, in both cases of non-cooperative behavior and full cooperation. Moreover, they emphasize the controversial nature of this effect for policy making.

In this paper we contribute to the literature by proposing a full-fledged multi-country dynamic general equilibrium model to address the optimal combination of domestic policy instruments, pollution mitigation, adaptation to the degraded state of the environment, and capital accumulation. In particular, we aim to investigate how the optimal policy depends on the stage of development of a country and its position on the international area. Total factor productivity and the rate of time preference are among the main characteristics of a country's stage of development, and its power in international negotiations can be represented by the country's contribution to the global pollution flow. Also, despite the fact that there clearly exist big polluters and small polluters, there is no straight link between the amount of pollution and the stage of development. A developed country may be a small polluter (*e.g.* Switzerland, the Netherlands, Singapore, Belgium) while a developing country may well be a big polluter (*e.g.* China, India, Brazil).[3] We will study how such heterogeneities affect domestic policies.

For pedagogical motives, before building the multi-country model we will start with a simpler one-country model with an external pollution flow. It will highlight some key preliminary results that will be useful in understanding the multi-country model.

3. A single country in a global environment

We consider a country that is a part of the larger multi-country world and aggregate the rest of the world into a single exogenous zone. The country under study

[3] Some countries contribution to world greenhouse gases emissions in 2006 (in million tons of CO_2 equivalent for all GHGs, and in percent): USA 7,017.3 (24.5%); Russia Federation 2,190.2 (7.6%); Belgium 136.9 (0.5%); Switzerland 53.2 (0.2%); source: UNFCCC, FCCC/SBI/2008/12. China 3,649.8 (12.7%); Brazil 1,477.1 (5.1%); India 1,228.5 (4.2%); South Africa 361.2 (1.2%); Singapore 26.8 (0.1%); source UNFCCC, FCCC/SBI/2005/18/Add.2.

determines its optimal national policy by taking the rest of the world as given. It thus represents a Nash equilibrium constrained by exogenous players, *i.e.* a game where one player (it could be generalized to *n* endogenous players) determines its optimal strategy while all other players have fixed strategies. As it is commonly assumed in the literature, the only interaction between countries is the global climate. So, the rest of the world can be represented as an exogenous pollution flow. This flow complements the endogenous country's contribution to the global pollution, as the sum of the two matches the world's pollution flow. Interestingly, such a simple modeling framework will allow us to analyze how optimal domestic policies are shaped by the size of the country under study. This is an innovative and convenient way of addressing asymmetry among countries in global pollution games: to what extent the optimal domestic policy would change with the contribution of the country to global pollution?[4]

3.1. Economic-environmental model of a country with external pollution stock

As in Bréchet *et al*. (2013), the endogenous country is described by the Solow-Swan one-sector model with a Cobb-Douglas technology. A benevolent social planner allocates the aggregate final product Y across consumption C, investment I_K into physical capital K, investment I_D into environmental adaptation D, and pollution mitigation expenditures B. The intertemporal utility depends positively on the consumption C, negatively on pollution P, and positively on adaptation D. The programme of the social planner is to maximize the utility of the infinitely lived representative household:

$$\max_{I_K, I_D, C} \int_0^\infty e^{-\rho t} U[C(t), P(t), D(t)] dt \tag{1}$$

$$I_K(t) \geq 0, \qquad I_D(t) \geq 0, \quad C(t) \geq 0,$$

subject to the following constraints:

$$Y(t) = AK^{\alpha}(t) = I_K(t) + I_D(t) + B(t) + C(t), \tag{2}$$

$$K'(t) = I_K(t) - \delta_K K(t), \qquad K(0) = K_0, \tag{3}$$

$$D'(t) = I_D(t) - \delta_D D(t), \qquad D(0) = D_0, \tag{4}$$

where $\rho > 0$ is the rate of time preference, $A > 0$ and $0 < \alpha < 1$ are parameters of the Cobb-Douglas production function, $\delta_K \geq 0$ and $\delta_D \geq 0$ are deterioration rates of physical capital and adaptation capital. Eq. (2) is the economy budget constraint. Eqs. (3) and (4) describe capital accumulation of productive physical capital and adaptation capital. It is assumed that economic activity Y increases the pollution stock P, which negatively enters the utility function (1), while mitigation expenditures B allow to partially alleviating this adverse impact of the pollution stock. It must be stressed that the endogenous economy only contributes to a part of the worldwide pollution flow, while it suffers from the global

[4]It must be stressed that "country size" and "country's contribution to climate change" are two different realities in an asymmetric world. Two countries with similar GDPs may well have very different pollution levels. Only the latter matters in our multi-country setting. For example, Canada and Spain had almost the same GDP level in 2011 (around 1400 billion US$, source: OECD) while GHGs emissions were twice larger in Canada (source: UNFCCC).

pollution stock. The externality typical to a public good appears here, as well as the asymmetry between adaptation and mitigation at the country level.

As explained in the beginning of this Section, the rest of the world is represented by an exogenous pollution flow, denoted by Z. The dynamics of the global pollution stock P is given by:

$$P'(t) = -\delta_P P(t) + \gamma[Y(t)/B(t) + Z(t)], \qquad P(0) = P_0, \tag{5}$$

where $\gamma > 0$ is the emission factor (the environmental dirtiness of the economy) and $\delta_P > 0$ is the natural pollution decay rate.[5] The pollution flow of the endogenous economy can be mitigated by mitigation spending B, as in Gradus and Smulders (1993). In this setting, by choosing Z, we are able to analyze how the optimal environmental policy of the country under study depends on its share in the global pollution flow. So, one of the key innovative features of this model is to endogenize both mitigation and adaptation as domestic policy measures in the presence of an external exogenous pollution stock.

Let us consider that the utility function (1) is as follows:

$$U(C, P, D) = U_1(C) - U_2(P, D) = \ln C - \eta(D)\frac{P^{1+\mu}}{1+\mu}, \tag{6}$$

where the function $\eta(D)$ represents the *vulnerability* of the economy to pollution and the parameter $\mu > 0$ reflects the increasing marginal disutility of pollution. Let us precise our assumptions on these functions.

In the environmental game theory literature (*e.g.*, Breton *et al*. 2006, Fanokoa *et al*. 2011, Legras and Zaccour 2011), U_1(C) is considered as the net revenue (gross revenue minus production cost) and $U_2(P)$ is as a damage function (the cost of environmental damage to the economy). Both are usually assumed to be quadratic or linear, but it will not necessarily be the case in our setting. Adaptation expenditures D enter the economy as a means to reduce the environmental vulnerability of the economy $\eta(D)$, *i.e.*, the adverse economic costs of a given pollution stock level. This function deserves some attention. It is natural to assume that vulnerability is maximal when no adaptation measures are taken, $\eta_{\max} = \eta(0)$, and that vulnerability gradually decreases to some minimum level when the adaptation efforts tend to infinity, $\eta_{\min} = \eta(\infty) > 0$. The potential gap $\eta_{\max} - \eta_{\min}$ represents the range of physical adaptation opportunities in the economy as it depends on the geographical or infrastructural characteristics of the country. In between this physical gap, the economic concept of efficiency must be introduced. It is done by the parameter a, which reflects the *marginal efficiency* of adaptation. In the remainder of the paper the functional form of effective adaptation will be as follows:

$$\eta(D) = \eta_{\min} + (\eta_{\max} - \eta_{\min})e^{-aD}, \quad \eta_{\max} > \eta_{\min} > 0, \quad a > 0. \tag{7}$$

We are now equipped with the model of a country that confronts the global climate change, for which it is only partially responsible, and chooses its optimal climate

[5]For tractability reasons, we assume that γ is the same in the country under study and in the rest of the world.

policy, which consists of emission mitigation and adaptation spending. To analyze the country's optimal domestic policy, we will characterize the steady state economy.

3.2. Steady-state analysis

The optimization problem (1)-(5) includes three control variables I_K, I_D, C, and four state variables K, D, B, P, related by four constraints-equalities (2)-(5). In order to keep the analytic complexity feasible for the forthcoming multi-country case, we restrict ourselves to the steady–state analysis assuming $Z(t)$ = const. We also assume that capital depreciation is the same for physical and adaptation capital stocks ($\delta_K = \delta_D = \delta$). The structure of possible stationary solutions is described in the following lemma.

Lemma 1 (Steady state). *The optimization problem (1)-(7) possesses a stationary state* ($\overline{K}$, $\overline{B}$, $\overline{C}$, $\overline{D}$, $\overline{P}$)*:*

$$\overline{B} = A\overline{K}^{\alpha} - \overline{K}(\rho+\delta)/\alpha, \tag{8}$$

$$\overline{C} = \overline{K}(\rho+\delta)/\alpha - \delta(\overline{K}+\overline{D}), \qquad \bar{I}_K = \delta\overline{K}, \qquad \bar{I}_D = \delta\overline{D}, \tag{9}$$

$$\overline{P} = \frac{\gamma}{\delta_P}\left(\frac{A}{A-\overline{K}^{1-\alpha}(\rho+\delta)/\alpha} + Z\right), \tag{10}$$

where $\overline{K}$ *,* $0<\overline{K}<\left(\alpha A/(\rho+\delta)\right)^{1/(1-\alpha)}$ *and* $\overline{D}\geq 0$ *are determined in the following way.*

First, the optimal capital stock $\overline{K}>0$ *when optimal adaptation is zero (*$\overline{D}=0$*) is the unique solution of the following equation:*

$$\left(\frac{A}{A-\overline{K}^{1-\alpha}(\rho+\delta)/\alpha} + Z\right)^{-\mu} \frac{(A-\overline{K}^{1-\alpha}(\rho+\delta)/\alpha)^2}{\overline{K}^{1-\alpha}} = \frac{\rho\gamma^{1+\mu}A^{1+\mu}\eta_{\max}}{\alpha(\delta_P+\rho)\delta_P{}^{\mu}}\left(\frac{\rho+\delta}{\alpha} - \delta\right), \tag{11}$$

provided the calculated value $\overline{K}$ *is small enough. Otherwise, positive adaptation and capital stocks* $\overline{K}>0$ *and* $\overline{D}>0$ *are determined by the following system of two nonlinear equations:*

$$\begin{aligned}&\left(\frac{A}{A-\overline{K}^{1-\alpha}(\rho+\delta)/\alpha} + Z\right)^{-\mu} \frac{(A-\overline{K}^{1-\alpha}(\rho+\delta)/\alpha)^2}{\overline{K}^{-\alpha}} \\ &= \frac{\rho\gamma^{1+\mu}A}{\alpha(\delta_P+\rho)\delta_P{}^{\mu}}\left(\frac{\rho+\delta}{\alpha}\overline{K} - \delta\overline{K} - \delta\overline{D}\right)\left[\eta_{\min} + (\eta_{\max}-\eta_{\max})e^{-a\overline{D}}\right]\end{aligned} \tag{12}$$

$$\left(\frac{\rho+\delta}{\alpha}\overline{K} - \delta\overline{K} - \delta\overline{D}\right)a(\eta_{\max}-\eta_{\max})e^{-a\overline{D}}\frac{\gamma^{\mu+1}}{\rho\delta_P{}^{\mu+1}(\mu+1)} = \left(\frac{A}{A-\overline{K}^{1-\alpha}(\rho+\delta)/\alpha} + Z\right)^{-\mu-1} \tag{13}$$

Proof: see Appendix.

Analyzing the existence of positive solutions for $\overline{D}$ and $\overline{K}$ in the two nonlinear equations (12)-(13) is not straightforward. In particular, it turns out to be extremely difficult when $\delta > 0$, even with $Z = 0$ (see Yatsenko *et al*. 2014). So we restrict ourselves to the case $\delta = 0$ of zero deterioration.

At $\delta = 0$, solving the system of two equations (12)-(13) in Lemma 1 is reduced to a single equation. Indeed, Eq. (13) becomes

$$a(\eta_{\max} - \eta_{\min})e^{-a\overline{D}} \frac{\gamma^{\mu+1}\overline{K}}{\alpha\delta_P^{\mu+1}(\mu+1)} = \left(\frac{A}{A - \overline{K}^{1-\alpha}(\rho)/\alpha} + Z\right)^{-\mu-1} \quad (14)$$

and can be solved for D at a given $\overline{K}$ as:

$$D(\overline{K}) = \frac{1}{a}\ln\left[\frac{a(\eta_{\max} - \eta_{\min})\gamma^{\mu+1}\overline{K}}{\alpha(\mu+1)\delta_P^{\mu+1}}\left(\frac{A}{A - \overline{K}^{1-\alpha}\rho/\alpha} + Z\right)^{\mu+1}\right]. \quad (15)$$

This leads us to the first proposition.

Proposition 1 (Optimal adaptation and capital stocks at steady-state).

Let $\delta = 0$. If the unique solution $\hat{K} > 0$ of the equation

$$\frac{A\alpha}{\hat{K}^{1-\alpha}\rho}\left(1 - \frac{\hat{K}^{1-\alpha}\rho}{A\alpha}\right)^{\mu+2}\left[1 + Z\left(1 - \frac{\hat{K}^{1-\alpha}\rho}{A\alpha}\right)\right]^{-\mu} = \frac{\eta_{\max}\gamma^{1+\mu}}{(\delta_P + \rho)\delta_P^{\mu}} \quad (16)$$

is such that $D(\hat{K}) \leq 0$, then the optimal steady-state adaptation $\overline{D}$ is zero and the optimal capital level is $\overline{K} = \hat{K}$. Otherwise, the unique $\overline{K} > \hat{K}$ is found from the nonlinear equation:

$$\begin{aligned}\frac{A\alpha}{\overline{K}^{1-\alpha}\rho}\left(1 - \frac{\overline{K}^{1-\alpha}\rho}{A\alpha}\right)^{\mu+2} &= \frac{\eta_{\min}\gamma^{1+\mu}}{(\delta_P + \rho)\delta_P^{\mu}}\left[1 + Z\left(1 - \frac{\overline{K}^{1-\alpha}\rho}{A\alpha}\right)\right]^{\mu} \\ &+ \frac{\alpha(\mu+1)}{a\overline{K}(1 + \rho/\delta_P)}\left(1 - \frac{\overline{K}^{1-\alpha}\rho}{A\alpha}\right)^{\mu+1}\left[1 + Z\left(1 - \frac{\overline{K}^{1-\alpha}\rho}{A\alpha}\right)\right]^{-1}\end{aligned} \quad (17)$$

And the optimal adaptation $\overline{D}$ is positive and given by (15).

Proof: see Appendix.

Eq. (15) shows that if the capital stock $\overline{K}$ is too small, then the optimal adaptation level should be negative (because of the logarithm), which is not possible. Thus, the optimal solution is no adaptation. Such cases will occur when the economy under analysis is very poor. As a consequence, the vulnerability of the economy is maximal $\eta(D) = \eta(0) = \eta_{\max}$ because the optimal adaptation level is zero. If the opportunities for adaptation are too narrow or if the economy is too poor, then it is optimal not to spend money on adaptation at all but to focus on mitigation. This preliminary result shows that it is optimal to invest in adaptation only under some balance between three ingredients, each of which has an economic/environmental rationale. First, the wealth of the economy, represented by the level of its capital stock $\overline{K}$, must be considered. A wealthier economy has a stronger incentive to invest in adaptation, and it is optimal not to invest in adaptation if the economy is too poor. Second, the technological potential for adaptation $a(\eta_{\max} - \eta_{\min})$ must be wide enough. This potential naturally depends on each country's geographical and physical characteristics. A country located is an area highly sensitive to global warming (e.g., near oceans or mountains) is expected to offer a wider technological potential than others. Third, what we may call the *environmental dirtiness ratio* γ / δ_P also plays a key role. This ratio translates the fact that the actual detrimental impact of an economy on the environment depends not only on its polluting intensity γ but also on the natural decay rate of the pollution stock δ_P. So, the results gathered in Proposition 1 have important policy implications. By anticipating forthcoming results, the proposition also suggests interesting insights when cooperation among countries will be considered. It shows that the countries that remain highly vulnerable to climate change will be the less developed ones. These results will come out again later in the multi-country setting, with many new insights.

3.3. The optimal domestic policy

On the ground of Proposition 1 we can characterize the optimal climate policy of the country under study. To proceed further we need a corner stone, and this one will prove to be a key indicator of both the vulnerability of the economy and its pressure on the environment. This indicator is required for mathematical and is economically grounded. Every economy must in fact be characterized in both dimensions: it is vulnerable to pollution, but it also contributes to it. So, reducing pollution is a benefit (avoided damages) as well as a cost (mitigation efforts). The optimal policy mix between the two depends on both these physical characteristics and their economic counterparts and each country's strategic position depends on both dimensions. So, we shall define what we call a *κ-indicator of environmental harm and vulnerability.* Naturally, this indicator is endogenous as depends on the country's adaptation efforts. It writes as follows.

Definition 1. *The κ-indicator of environmental harm and vulnerability is defined as:*

$$\kappa(\eta) = \frac{\eta\gamma^{1+\mu}}{(\delta_P + \rho)\delta_P{}^{\mu}}. \tag{18}$$

The reader interested in the mathematical reasoning and importance of function (18) for the proofs is sent to Appendix. Beyond its mathematical properties, the indicator offers quite appealing economic intuitions.[6] The *κ-indicator* defined by equation (18) combines both the pressure of human activity on the environment (the pollution intensity of production γ) and the pressure of the environment on welfare (the environmental

[6] This indicator was first introduced in Bréchet *et al.* (2013).

vulnerability of the economy η).[7] An economy can be highly vulnerable to climate change because of the physical sensitivity to impacts (geography, infrastructure, location…) and/or subjective reasons (disutility), and/or its polluting intensity, which will influence its mitigation cost (through the opportunity cost of mitigation). This synthetic indicator captures the whole picture. It is important to stress again that the *κ-indicator* is endogenous. It depends on the domestic policy and, in particular, on the adaptation efforts *D*. Even if the vulnerability of an economy is something given beforehand by country's physical characteristics, it is not gloom as it can be changed by an adequate adaptation policy. Because *D* is related to other policy instruments *B* and *K*, we cannot say that adaptation measures can be taken independently of other decisions.

Because the adaptation is bounded from below (no adaptation) and from above (full adaptation), the *κ-indicator* is also bounded. We can easily define the two boundaries $\kappa_{\min} < \kappa(\eta) \le \kappa_{\max}$ as cases where vulnerability is minimal and maximal, *i.e.*:

$$\kappa_{\min} = \kappa(\eta_{\min}) \text{ and } \kappa_{\max} = \kappa(\eta_{\max}). \tag{19}$$

The boundaries (19) are used in the proof of Proposition 1. In order to obtain approximate expressions for steady-state variables $\overline{K}$, $\overline{B}$, $\overline{C}$, $\overline{D}$, $\overline{P}$, let us consider two cases depending on whether the *κ-indicator* is large or small, defined as Case A and Case B below.

Case A reflects a (brown) economy that is both very polluting but also heavily impacted by the global pollution. This boils down to assume a lower bound for *κ*given by:

$$1 << \kappa_{\min} << (1+Z)\left(\frac{A}{\rho}a^{1-\alpha}\right)^{1/\alpha}. \tag{20}$$

The interpretation of the formal expression (20) of Case A is rather straightforward. The left inequality (20) imposes that the lower limiting value $\kappa_{\min}$ in (19) is large enough, which means that pollution impact is high and the economy cannot overcome all the adverse effects of pollution *even when all adaptation measures are implemented*. The second part of the inequality means that the ratio between the productivity level *A* and the discount factor *ρ*, and/or the adaptation efficiency *a*, and/or the external pollution are much larger than $\kappa_{\min}$. Although it really deserves to be documented for future researches, the USA or the UE would certainly match Case A. In Bréchet *et al*. (2013) we show that Case A is also rather realistic on the ground of current world aggregate data. If Case A holds, then the optimal steady state capital $\overline{K}$ is given by the approximate formula

$$\overline{K} \cong \left[\frac{\alpha A}{\kappa_{\min}\rho(1+Z)^{\mu}}\right]^{\frac{1}{1-\alpha}}. \tag{21}$$

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[7]In this sense, the *κ-indicator* represents a kind of theoretically reduced form of the DPSIR framework (Driving-Pressure-State-Impact-Response), showing that the interplay between the economy and the climate goes both ways (every economy is polluted and is a polluter at the same time) and combines both physical and subjective dimensions.

Here and thereafter, the notation $f(\varepsilon) \cong g(\varepsilon)$ means that $f(\varepsilon)=g(\varepsilon)[1+o(\varepsilon)]$ for some small parameter $0<\varepsilon<<1$and $f(\varepsilon)\rightarrow g(\varepsilon)$ when $\varepsilon\rightarrow 0$. The proof of (21) is analogous to Bréchet *et al*. (2013).

Case B describes a (green) economy with a lightly polluted environment, which boils down to assume:

$$\kappa_{\max} << 1 \tag{22}$$

In this case, the upper bound of $\kappa_{\max}$ is not too large, which means that the vulnerability is low even without any adaptation. For Case B's countries, the optimal steady state capital $\overline{K}$ is determined by the approximate formula:

$$\overline{K} \cong \left[\frac{\alpha A}{\rho}(1-\kappa_{\max})^{\frac{1}{\mu+2}}\right]^{\frac{1}{1-\alpha}} \tag{23}$$

By considering Cases A and B we are able to find the optimal steady-steady capital stock $\overline{K}$ from (21) or (23) as well as all the other steady-state variables $\overline{B}$, $\overline{C}$, $\overline{D}$, $\overline{P}$, which are explicitly determined by (8)-(10), (15) and Proposition 1. Equations (21) and (23) allow us to describe the optimal domestic climate policy of the country under study and to understand how it is shaped by its contribution to the global pollution flow.

It is first enlightening to consider a world economy, *i.e.* the case when Z= 0 (see Bréchet *et al*. (2013) for further details). Mitigation and adaptation turn out to be substitutable policy instruments. For a given country, allowing for adaptation reduces mitigation efforts, as it can naturally be expected. The country can support a stronger global warming (so a larger pollution stock) when there exist adaptation measures capable to alleviate the related adverse effects. The size of the economy is thus larger. More interesting is the fact that the optimal policy mix between adaptation and mitigation is shaped by country's wealth, in particular by its total factor productivity A. The optimal ratio D/B is bell-shaped: it is first increasing in A, and then decreasing. If the economy is too poor, optimal adaptation must be zero. As the country becomes richer, it should increase the share of adaptation in its policy mix, but after a while the contribution of adaptation should decrease and the one of mitigation should increase. A rich country should not spend too much on adaptation, but on mitigation. All these results hold for any $Z > 0$.

Let us now turn to the analysis of the influence of Z on the policy mix. The analysis of formulas (21) and (23) demonstrates how the optimal size of the economy, adaptation, and mitigation depend on the external pollution stock Z and the country's relative size (in terms of its contribution to the global pollution).

Proposition 2 (Optimal domestic policy *wrt* country's contribution to pollution)

(i) The larger the country's share in global pollution stock is (small Z), the larger its mitigation spending $\overline{B}$*, capital stock* $\overline{K}$*, output* $\overline{Y}$*, and consumption* $\overline{C}$ *levels are;*

(ii) If the κ-indicator is small (κ_{max}<<1), then the influence of Z on the domestic policy is weak; if the κ-indicator is high ($\kappa_{\min} >> 1$), then capital $\overline{K}$ decreases in Z following (21), the consumption $\overline{C}$ is proportional to $\overline{K}$, while the output and mitigation expense decrease as $\overline{K}^{\alpha}$;

(iii) The optimal adaptation $\overline{D}$ starts earlier and increases with Z at κ_{max}<<1. In the case of a high κ-indicator ($\kappa_{\min} >> 1$), the optimal adaptation $\overline{D}$ decreases with Z when $\mu <$ $(1-\alpha)/\alpha$, and increases otherwise.

Proof. See Appendix.

The larger the country's contribution to global warming, the better the country can control the global pollution stock by mitigating its own pollution and thus preserve its own welfare. So, there is a strong incentive to spend money on mitigation rather than on adaptation. Then, more income is required, so more capital and output. As a result, the size of the economy becomes larger. Naturally, this dependence is stronger when the pollution vulnerability is essential.

As highlighted in the item (*iii*) of Proposition 2, the impact of *Z* on the optimal adaptation level $\overline{D}$ is less straightforward. It goes through two channels. Indeed, the optimal $\overline{D}$ is smaller (or even zero) if the economy is too poor ($\overline{K}$ very small). But on the other hand, *Z* directly increases pollution, and correspondingly the adaptation efforts by (15). The final effect depends on the κ-indicator and parameters μ and α. In particular, it is positive for a small κ-indicator. Then $\overline{K}$ does not depend on *Z* by (23), therefore, increasing *Z* directly increases adaptation. If the κ-indicator is large, both situations are possible and the key parameter is the pollution disutility μ. If μ is small (*i.e.* the disutility of pollution in (6) is almost linear), then the optimal adaptation level *D* decreases as the country's contribution to pollution decreases (larger *Z*). But if the pollution disutility is large enough, $\mu > (1-\alpha)/\alpha$, then the optimal adaptation level *D* increases with *Z*. The above condition on μ roughly corresponds to $\mu > 0.6$ in the current world situation assuming the share of labor in output $\alpha = 2/3$. In other words, increasing the relevance of pollution in society's objective leads to an increase of adaptation in absolute units even when the economy becomes weaker and all other economic characteristics become smaller (at a larger Z).

Correspondingly, the impact of the country's size on the optimal ratio *D/B* is stronger as μ is larger. Even when μ is small, then *Z* does not affect *B* and *K* by (21), while it still impacts the optimal adaptation level *D*. The reaction of optimal adaptation is thus much more complex. This will explain some of our results in the multi-country setting. We shall notice that, if the country size is small, then its welfare may become negative because of climate change adverse effects (the pollution *P* increases while both $\overline{K}$ and $\overline{C}$ become small for large *Z*).

4. The multi-country case

Let us now explore the case of a multi-country world. For the sake of readability, we will first consider only two countries, and the generalization to *n* countries will be discussed in the last subsection. We are interested in comparing the optimal domestic climate policies in two scenarios: when each country maximizes its own welfare, and when both countries coordinate on the policy. The former is known as a non-cooperative Nash equilibrium, the latter as a cooperative solution. Because the pollution stock is common to both countries, it is clear that the Nash equilibrium is sub-optimal. The cooperative solution, on the other side, leads the world to a first best situation. Our purpose is not to analyze game theoretical issues related to cooperation (Breton *et al*. 2006, Fanokoa *et al*. 2011, Legras and Zaccour 2011), but rather to scrutinize how domestic policies are shaped by cooperation. The usual result in the literature is that non-cooperation leads to too low emission mitigation compared to what is socially optimal. We will see in this section that much more results can emerge when comparing Nash and cooperation. Actually, a general equilibrium standpoint allows showing that countries may look completely different between the two situations. This is not just a question of mitigation level, as usually discussed in the literature, but also of adaptation, capital stock and consumption levels. We start by characterizing the two scenarios (non-cooperation, then cooperation) and the comparison between the two will follow.

4.1. The non-cooperative scenario

Let us consider an economic-environmental system (the world) that consists of two countries that share the same pollution stock: Country 1 and Country 2. The external emission flow Z now becomes endogenous and results from the economic activity of Country 2:

$$Z(t) = Y_2(t)/B_2(t). \tag{24}$$

We assume that countries do not cooperate. Each one decides on its own policy by maximizing its utility function, taking the policy of the other country as given. The corresponding optimization problem is as follows:

$$\max_{I_{Ki}, I_{Di}, C_i,} \int_0^\infty e^{-\rho t}\left[\ln C_i(t) - \eta_i(D_i(t))\frac{P(t)^{1+\mu}}{1+\mu}\right]dt\,, \tag{25}$$

under the constraints

$$I_{Ki}(t) \geq 0, \qquad I_{Di}(t) \geq 0, \qquad C_i(t) \geq 0,$$

$$Y_i(t) = A_i K_i^{\alpha_i}(t) = I_{Ki}(t) + I_{Di}(t) + B_i(t) + C_i(t), \tag{26}$$

$$K_i'(t) = I_{Ki}(t) - \delta_{Ki} K_i(t), \qquad K_i(0) = K_{0i}, \tag{27}$$

$$D_i'(t) = I_{Di}(t) - \delta_{Di} D_i(t), \qquad D_i(0) = D_{0i}, \quad i = 1,2, \tag{28}$$

$$P'(t) = -\delta_P P(t) + \gamma A_1 K_1^{\alpha_1}(t)/B_1(t) + \gamma A_2 K_2^{\alpha_2}(t)/B_2(t), \qquad P(0) = P_0. \tag{29}$$

It is the dynamic continuous game of two players (Countries 1 and 2) with the pay-off functions (25), i=1,2. Each player solves the optimization problem (25)-(29) with its own endogenous variables: consumption C_i, investments in physical capital and in adaptation I_{Ki}, I_{Di}, and mitigation B_i, i = 1,2. The externality is the global pollution stock P.

As the solution strategy for this game we use the classic *open-loop Nash equilibrium* (OLNE), which is a pre-commitment strategy (Long 2010). It assumes that each player maximizes its own payoff (25) by taking the other player's OLNE decision as given.[8] As before, we restrict ourselves to the comparative static analysis of the problem (25)-(29) and assume zero deterioration for the capital stocks in both countries: $\delta_{Ki} = \delta_{Di} = 0$. Similarly to Lemma 1, possible steady states $\overline{K}_i$, $\overline{B}_i$, $\overline{C}_i$, $\overline{D}_i$, $\overline{P}$ for each player i =1,2 should satisfy (19)-(13) at $Z=\overline{Y}_{3-i}/\overline{B}_{3-i}$ or the following system of nine equations

$$\overline{B}_i = A_i\overline{K}_i^{\alpha_i} - \overline{K}_i\rho/\alpha_i, \tag{30}$$

$$\overline{C}_i = \overline{K}_i\rho/\alpha_i, \tag{31}$$

$$\overline{D}_i = \max\left\{0, \frac{1}{a_i}\ln\frac{a_i(\eta_{\max i} - \eta_{\min i})\overline{K}_i\overline{P}^{\mu+1}}{\alpha_i(\mu+1)}\right\}, \quad i=1,2, \tag{33}$$

$$\overline{P} = \frac{\gamma}{\delta_P}\left(\frac{A_1}{A_1 - \overline{K}_1^{1-\alpha_1}\rho/\alpha_1} + \frac{A_2}{A_2 - \overline{K}_2^{1-\alpha_2}\rho/\alpha_2}\right), \tag{32}$$

$$\frac{\gamma\overline{P}^{\mu}}{(\delta_P+\rho)}[\eta_{\min i} + (\eta_{\max i} - \eta_{\min i})e^{-a_i\overline{D}_i}] = \frac{[\alpha_i A_i - \overline{K}_i^{1-\alpha_i}\rho]^2}{\rho\alpha_i A_i\overline{K}_i^{1+\alpha_i}}, \quad i=1,2, \tag{34}$$

with respect to $\overline{K}_1$, $\overline{K}_2$, $\overline{B}_1$, $\overline{B}_2$, $\overline{C}_1$, $\overline{C}_2$, $\overline{D}_1$, $\overline{D}_2$, and $\overline{P}$.

The existence of the Nash equilibrium for continuous dynamic games is not guaranteed. In our game (25)-(29), it depends on solvability of the nonlinear system (30)-(34). Solving the game with asymmetric players is not feasible. So we will consider the symmetric case (two identical countries). Let:

$$A_1=A_2,\ \alpha_1=\alpha_2,\ \eta_{\min 1} = \eta_{\min 2},\quad a_1=a_2,\quad b_1=b_2. \tag{35}$$

At (35), if the OLNE equilibrium state exists, it is the same for both players: $\overline{K}_1=\overline{K}_2=\overline{K}_N$, $\overline{B}_1=\overline{B}_2=\overline{B}_N$, $\overline{C}_1=\overline{C}_2=\overline{C}_N$, $\overline{D}_1=\overline{D}_2=\overline{D}_N$, where the subscript N stands for Nash. Then, the equations (30)-(34) for the unknown $\overline{K}_N$, $\overline{B}_N$, $\overline{C}_N$, $\overline{D}_N$, and $\overline{P}_N$ lead to

$$\overline{B}_N = A\overline{K}_N^{\alpha} - \overline{K}_N\rho/\alpha, \tag{36}$$

$$\overline{C}_N = \overline{K}_N\rho/\alpha, \tag{37}$$

$$\overline{P}_N = \frac{2\gamma}{\delta_P}\left(\frac{A}{A - \overline{K}_N^{1-\alpha}\rho/\alpha}\right), \tag{38}$$

$$\overline{D}_N = \max\left\{0, \frac{1}{a}\ln\frac{a(\eta_{\max} - \eta_{\min})\overline{K}_N\overline{P}_N^{\mu+1}}{\alpha(\mu+1)}\right\}. \tag{39}$$

[8]Another more recent strategy for dynamic games is the feedback or Markov-perfect Nash equilibrium strategy, when the decision depends on a current state. A technical advantage of OLNE is that it is relatively easy to calculate (Long 2010), which is imperative in such a complicated model as (25)-(29). We discuss other more practical reasons for choosing OLNE over the feedback strategy later in Section 3.4.

where $\overline{K}_N$>0 is found from the nonlinear equation (16) at $\overline{D}_N$=0 and $Z = A\overline{K}_N^{\alpha} / \overline{B}_N$ or from (17) at $\overline{D}_N$>0,$Z = A\overline{K}_N^{\alpha} / \overline{B}_N$.

As in Section 2, if condition (20) holds then the unique optimal $\overline{K}_N$ exists and is determined as:

$$\overline{K}_N \cong \left[\frac{\alpha A(\rho + \delta_P)\delta_P^{\ \mu}}{\eta_{\min}\gamma^{\mu+1}2^{\mu}} \right]^{\frac{1}{1-\alpha}} = \overline{K} / 2^{\mu/(1-\alpha)}. \tag{40}$$

If (22) holds: $\kappa_{\max} << 1$, then the optimal $\overline{K}_N$ is determined by the same approximate formula (23), *i.e.*, $\overline{K}_N \cong \overline{K}$.

The set of the same strategies $\overline{K}_N$, $\overline{B}_N$, $\overline{C}_N$, $\overline{D}_N$ for both players constitutes theopen-loop Nash equilibrium strategy in the game (25)-(29). Using (7) and (18), the corresponding optimal vulnerability function and κ–indicator are calculated as

$$\overline{\eta}_N = \eta(\overline{D}_N), \qquad \kappa_N = \kappa(\overline{\eta}_N). \tag{41}$$

It is clear that the Nash equilibrium does not yield the best cumulative payoff for the players. In many situations, the players might improve their own payoffs, as well as global welfare, by following some cooperative strategies. The next section considers that scenario.

4.2. The cooperative scenario

In this section we analyze the case of a full international cooperation in our two-country world. It means that the countries coordinate the policy that maximizes their joint welfare. We assume that a benevolent social planner represents a multinational governmental body with complete control on the environmental policies of Countries 1 and 2. The corresponding optimization problem is as follows:

$$\max_{I_{K1}, I_{D1}, C_1, I_{K2}, I_{D2}, C_2} \int_0^{\infty} e^{-\rho t} \left[\ln C_1(t) + \ln C_2(t) - \eta(D_1(t)) \frac{P(t)^{1+\mu}}{1+\mu} - \eta(D_2(t)) \frac{P(t)^{1+\mu}}{1+\mu} \right] dt, \tag{42}$$

$$I_{K_i}(t) \geq 0, \qquad I_{D_i}(t) \geq 0, \quad C_i(t) \geq 0,$$

under the constraints (26)-(29).

This problem is an extension of the optimization problem (1)-(6) with a double set of endogenous variables: the consumptions C_1 and C_2, the investments I_{K_1}, I_{K_2}, I_{D_1}, I_{D_2}, and the mitigation expenses B_1 and B_2 of Countries 1 and 2 respectively. The objective function describes the joint cumulative payoff of both countries. In such a case, the externality associated to the global pollution stock P is fully internalized and the outcome is the first best. The optimization problem includes six decision variables I_{K_1}, I_{K_2}, I_{D_1}, I_{D_2}, C_1, C_2, seven state variables K_1, K_2, D_1, D_2, B_1, B_2, P, and nine constraints-equalities (26)-(29). Despite its double size, it can be treated analogously to the problem (1)-(6). Assuming $\delta_{K_i} = \delta_{D_i} = \delta$ and providing the comparative static analysis, we obtain the following interior first order conditions for nine steady-state variables $\overline{K}_i$, $\overline{B}_i$, $\overline{C}_i$, $\overline{D}_i$, i = 1,2, and $\overline{P}$:

$$\alpha_i A_i \overline{K}_i^{\alpha_i} - \alpha_i \overline{B}_i = \overline{K}_i(\delta + \rho), \tag{43}$$

$$A_i \overline{K}_i^{\alpha_i} = \delta\overline{K}_i + \delta\overline{D}_i + \overline{B}_i + \overline{C}_i, \tag{44}$$

$$-\eta_i'(\overline{D}_i)\frac{\overline{P}^{\mu+1}}{(1+\mu)} = \frac{(\delta+\rho)}{\overline{C}_i}, \quad i = 1,2, \tag{45}$$

$$\overline{P}^{\mu}[\eta_1(\overline{D}_1) + \eta_2(\overline{D}_2)] = \frac{(\delta_P + \rho)\overline{B}_1^{\,2}}{\gamma A_1 \overline{K}_1^{\alpha_1}\overline{C}_1} = \frac{(\delta_P + \rho)\overline{B}_2^{\,2}}{\gamma A_2 \overline{K}_2^{\alpha_2}\overline{C}_2}, \tag{46}$$

$$\delta_P \overline{P} = \gamma\left(\frac{A_1\overline{K}_1^{\alpha_1}}{\overline{B}_1} + \frac{A_2\overline{K}_2^{\alpha_2}}{\overline{B}_2}\right). \tag{47}$$

An analysis of the system (43)-(47) indicates the way of its sequential solution, which is the extension of the technique used in Section 2. Namely, assuming δ =0, the steady state $\overline{K}_i$, $\overline{B}_i$, $\overline{C}_i$, $\overline{D}_i$, i =1,2, $\overline{P}$ satisfies the system of nine nonlinear equations (30)-(33) and

$$\frac{\gamma\overline{P}^{\mu}}{(\delta_P + \rho)}\sum_{i=1}^{2}[\eta_{\min i} + (\eta_{\max i} - \eta_{\min i})e^{-a_i\overline{D}_i}] = \frac{[\alpha_i A_i - \overline{K}_i^{1-\alpha_i}\rho]^2}{\rho\alpha_i A_i \overline{K}_i^{1+\alpha_i}}, \qquad i = 1,2. \tag{48}$$

This system differs from the Nash equilibrium case only by the equation (48). Substituting the expressions of $\overline{D}_1$, $\overline{D}_2$ and $\overline{P}$ via $\overline{K}_1$ and $\overline{K}_2$ into (48), we obtain two nonlinear equations with respect to $\overline{K}_1$ and $\overline{K}_2$. This system of two equations is an analogue of the equation (14) for $\overline{K}$ in the one country case. The solution is simple in the case (35) of symmetric countries. Then, by symmetry considerations, the steady state satisfies conditions $\overline{K}_1=\overline{K}_2=\overline{K}_{CO}$, $\overline{B}_1=\overline{B}_2=\overline{B}_{CO}$, $\overline{C}_1=\overline{C}_2=\overline{C}_{CO}$, $\overline{D}_1=\overline{D}_2=\overline{D}_{CO}$, where the subscript CO stands for "Cooperation". Substituting the last expressions into the system (40)-(43),(66), we obtain the same equations (8)–(13) for the unknown $\overline{K}_{CO}$, $\overline{B}_{CO}$, $\overline{C}_{CO}$, $\overline{D}_{CO}$, $\overline{P}_{CO}$, in which $\delta = 0$, $Z = 0$,butthe coefficient γ is replaced by 2γ.

As in Section 2, if condition (20) holds, then the unique optimal $\overline{K}_{CO}$ is found as

$$\overline{K}_{CO} \cong \left[\frac{\alpha A(\rho + \delta_P)\delta_P^{\ \mu}}{\rho\eta_{\min}(2\gamma)^{\mu+1}}\right]^{\frac{1}{1-\alpha}} = \overline{K}/2^{(\mu+1)/(1-\alpha)} = \overline{K}_N/2^{1/(1-\alpha)}. \tag{49}$$

If (22) holds, $\kappa_{\max} << 1$, then the optimal $\overline{K}_N$ is determined by the approximate formula

$$\overline{K}co \cong \left[\frac{\alpha A}{\rho}(1 - 2^{\frac{\mu+1}{\mu+2}}\kappa_{\max}^{\ \frac{1}{\mu+2}})\right]^{\frac{1}{1-\alpha}} < \overline{K}_N. \tag{50}$$

After finding $\overline{K}_N$, the corresponding steady-state levels $\overline{B}_{CO}$, $\overline{C}_{CO}$, $\overline{D}_{CO}$, $\overline{P}_{CO}$, $\overline{\eta}_{CO}$, and κ_{CO} are also known, in particular,

$$\overline{\eta}_{CO} = \eta(\overline{D}_{CO}), \kappa_{CO} = \kappa(\overline{\eta}_{CO}). \tag{51}$$

We can now compare the optimal policy mix in the non-cooperative and cooperative scenarios.

4.3. Comparing cooperative and non-cooperative scenarios in terms of domestic policies

The comparison between the two scenarios will be carried out by comparing expressions (36)-(40) (Nash) and (49) (cooperation). This will confirm a couple of expected results, but also yield many unexpected ones. A naturally expected result is that pollution is too high in the non-cooperative scenario compared to the first best. Interestingly, the reasons why it is the case are not trivial at all. Namely, the first important result is that the size of economies sharply differs between two scenarios. This is summarized in the following proposition.

Proposition 3 (Size of the economy). *The optimal steady state capital level is always larger in the non-cooperative case than under cooperation:* $\overline{K}_N > \overline{K}_{CO}$. *If the κ-indicator of environmental harmfulness is small (*$\kappa_{\max} << 1$*), then the difference is small (*$\overline{K}_N \cong \overline{K}_{CO}$*); if the κ-indicator is large, then the difference is large. Formally, if the condition (20) holds, then:*

$$\overline{K}_N \cong 2^{1/(1-\alpha)}\overline{K}_{CO}, \quad \overline{Y}_N \cong 2^{\alpha/(1-\alpha)}\overline{K}_{CO}. \tag{52}$$

Proposition 3 states that the size of the economy is always too large in Nash equilibrium. This result will drive many other ones, as we will see later in this section. In other words, the lack of cooperation does not only lead to too much pollution but also (and maybe more importantly) to over accumulation of capital. Actually, the whole economy is much too fat in Nash. And it is even worse when the economy environmental harmfulness is high. In fact, the interpretation of Proposition 3 is rather intuitive. If the environmental self–cleaning capability δ_P is strong and the emission impact factor γ and environmental vulnerability η are negligible, then the pollution hardly affects the optimal policy. Indeed, in the case of a small $\kappa_{\max}$(i.e.,$\eta\gamma^{\mu+1} << \rho\delta_P{}^{\mu}$), the Nash equilibrium and cooperative optimal strategies are similar and do not depend on environmental parameters. This property is illustrated in Figure 1, which also highlights that the gap between $\overline{K}_N$ and $\overline{K}_{CO}$ monotonically increases from zero to the maximal factor $2^{1/(1-\alpha)}$ as the environmental harmfulness increases. Figure 1 shows that it is optimal to shrink the environmentally vulnerable economy, which is intuitive, but it also reveals that the shrink is not strong enough under Nash. This occurs because countries are not able to effectively control the global pollution level when international cooperation fails.

In the case of large emission impact γ, environmental vulnerability η, economic and adaptation efficiencies A and a, and negligible environmental self–cleaning δ_P, the Nash value (50) of capital is $2^{1/(1-\alpha)}$ times larger than the optimal capital amount (49) in the cooperative optimization problem. In this case, the Nash output level $\overline{Y}$ is $2^{\alpha/(1-\alpha)}$ timesclarger than the optimal one in the cooperative case. This also reveals that consumption and adaptation levels are much larger in Nash (than what they are in the cooperative scenario), which seems to be good for welfare. However, the pollution level is so high that it compensates for these two components. By the end, the resulting welfare is smaller.

Let us now consider the climate policies and first concentrate on mitigation. In both scenarios, the optimal mitigation spending is determined by the same formula (30): it depends on the capital level only. So it can formally be analyzed separately from the adaptation decision. This does not mean that adaptation and mitigation are separate decisions (as we will see below), but it suggests that the policy-maker should try first to control the pollution flow (with mitigation spending) and then alleviates adverse impacts with adaptation. Mitigation $\overline{B}_N$ in Nash is thus larger than the optimal mitigation in cooperation $\overline{B}_{CO}$. Countries spend too much on mitigation to try to keep the pollution flow under control. This is in sharp contrast with the current literature: in Nash, mitigation efforts are too large in dollars because the economy is too fat. In a certain sense, the lack of cooperation on the environmental common draws to wasteful economies: too much production is required to finance too much mitigation. It can be noted that, due to our assumptions about the pollution motion law (6), the pollution flow Y/B cannot decrease down to zero, which is realistic for greenhouse gases.

What is the influence of country's characteristics (the productivity parameter A and impatience rate ρ) on the optimal domestic policy? Such an analysis remains qualitatively the same as in Section 2 in both non-cooperative and cooperative scenarios. The optimal policy mix between adaptation and mitigation $\overline{D}/\overline{B}$ is initially zero for very small A(no adaptation is optimal). Then it grows with A and decreases later producing an inverted U-shape. When adaptation is positive, the size of the economy is larger, the pollution stock is larger, and mitigation efforts are smaller compared to the case with no adaptation. So, the policy mix displays the same qualitative properties in both scenarios.

We know from equation (15) that adaptation is positive starting with some minimal capital threshold size. We also know that the capital sock is larger in Nash than in cooperation. This means that adaptation will start earlier, i.e., for poorer economies, in the absence of cooperation. This is an important result as it suggests that a large pollution stock is not the only reason why poor countries have to start adaptation. And a key policy implication is related to financial transfers among countries (adaptation funds): too much money is needed in developing countries for adaptation in absence of cooperation.

Another result of interest is the following. In Nash, the optimal policy mix $\overline{D}/\overline{B}$ will reach its maximum for weaker economies (compared to the cooperative case). This is also illustrated in Figure 2. This shows that a definitive difference between cooperation and non-cooperation does not only lie in mitigation efforts, but also on the whole domestic policy mix.

All these results are summarized in the following statement.

Proposition 4 (Optimal policy mix) *In both cooperative and non-cooperative scenarios, optimal adaptation is zero when the total factor productivity A is too small; then,* $\overline{D}/\overline{B}$ *increases with A and decreases later. In the absence of cooperation, adaptation becomes positive at smaller values of A and the maximum of* $\overline{D}/\overline{B}$ *is reached at smaller A than under cooperation.*

4.4. Generalization to *n* countries

Until now we restricted our analysis to a two-country case for the sake of readability. Generalizing our results to *n* symmetric countries is straightforward. Proposition 2 holds replacing 2 by *n*. In particular, the Nash equilibrium output $\overline{Y}$ will be $n^{\alpha/(1-\alpha)}$ times larger than the optimal output in the case of full cooperation. The Nash equilibrium capital $\overline{K}$ will be $n^{1/(1-\alpha)}$ times larger than the capital in cooperative case. In summary, the Nash strategy in a multi-country world under study involves overproduction, which leads to overconsumption, over-pollution and over-adaptation. The primary problem comes from overproduction that appears because the country controls only its own pollution emission (so, a decrease in production causes much smaller decrease of pollution emissions than in the cooperative scenario). The corresponding adaptation investment depends on both production and pollution, so over-adaptation is the result of overproduction. All the results proved in the two-country model hold for *n* symmetric countries.

4.5. A short discussion about open-loop versus Markov-perfect Nash equilibrium

There are several important reasons for choosing the *open-loop Nash equilibrium* (OLNE) strategy over the Markov-perfect (feedback) Nash equilibrium strategy (Long, 2010) in our model.

First of all, the players are countries and as such are a priori less manipulative and more committed to planned actions as compared to, say, separate firms or private agents. Second, the anticipatory nature of the majority of adaptation projects requires careful preliminary design and multi-year investments, which matches well the OLNE assumption that each player knows the other player's optimal strategy (which is the same as her own). For the same reason, we have chosen our adaptation control *D* as the stock of adaptation capital, which takes years to build. In the case of the feedback Nash equilibrium strategy, each player can instantaneously change their optimal decision if the measured value of the state variable (pollution in our case) deviates from its anticipatory optimal Nash value.

The other reason is *a posteriori*. The $2^{\alpha/(1-\alpha)}$–fold overproduction in the non-cooperative case under the assumption (20) seems quite extreme and demonstrates that our stylized model possibly omits some features of process such as capital deterioration, see (Yatsenko *et al*. 2014) for a more detailed discussion. On the other hand, it is well known that the Markov-perfect Nash equilibrium strategy leads to larger pollution emission and overproduction in pollution games than OLNE does (Long 2010, p. 10-12). It gives us a sensible motive to stay with OLNE in our adaptation-mitigation policy analysis.

5. Conclusion and rooms for research

In this paper we developed a multi-country dynamic general equilibrium model to understand how international cooperation shapes domestic policies. Our model is built upon the classic Solow-Swan framework and captures essential nonlinearities in production and pollution dynamics. Its contribution to the literature is in the following insights. First, the optimal mitigation effort is always positive for all involved countries.[9] Second, the optimal ratio between adaptation and mitigation is zero for poor countries, maximal for middle-income countries, and it decreases but remains positive as the country becomes richer. Buob and Stephan (2011) agree that the adaptation is zero for poor countries, but they obtain a polar result that the richest regions should invest in adaptation only. Third, the non-cooperative (Nash) strategy in the multi-country world leads to overproduction, overconsumption, over-pollution and over-adaptation in comparison to cooperative case. This result could not be displayed by Buob and Stephan (2011) because production is exogenous.

We shall notice that our analysis is limited to the symmetrical case (identical countries). Extending our model to a multi-country model with asymmetry among countries would be highly desirable to address strategic behavioral differences between rich and poor countries, but it raises additional mathematical challenges and we leave it for further research. Nevertheless, our modeling approach with an exogenous pollution flow proves to be an appealing simple way of introducing heterogeneity in terms of country size. Several rooms for model extensions can be borrowed from the environmental games, following, *e.g*., Fanokoa *et al*. (2011) or Eyland and Zaccour (2014). We are planning to consider a two-player asymmetric pollution-control differential game where one player is non-vulnerable to pollution. It may simplify analytics and lead to interesting insights. Another potential idea is to use a border tax instead of a cooperative international agreement (Eyland and Zaccour, 2014). In terms of Breton *et al*. (2006), our model describes an “autarky” adaptation. Its possible extension to access merits of cooperation is in considering the “joint implementation” when players can invest into adaptation at home and abroad (where adaptation costs are lower). Multiple interacting pollutants with synergetic effects can be considered as in Legras and Zaccour (2011).

[9] In contrary, in Buob and Stephan (2011), regions can invest in mitigation or in adaptation only (or neither in adaptation nor mitigation), and the regions completely switch from mitigation to adaptation as the number of regions becomes large, which does not happen in our model.

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Appendix.

Proof of Lemma 1is analogous to (Yatsenko *et al*. 2014) for the case $Z = 0$. The current-value Hamiltonian for the problem (1)-(7) is

$$H = e^{-\rho t}(\ln C - \eta(D)\frac{P^{1+\mu}}{1+\mu}) + \lambda_1(AK^\alpha - I_K - I_D - B - C)$$
$$+\lambda_2(-\delta_P P + \gamma AK^\alpha / B + \gamma Z) + \lambda_3(I_K - \delta K) + \lambda_4(I_D - \delta D) + \mu_1 I_K + \mu_3 I_D + \mu_2 C, \quad \text{(A1)}$$

where the dual variables λ_1, λ_2, λ_3, λ_4 are associated with equalities (2)-(5) and μ_1, μ_2, μ_3 reflect the irreversibility constraints. Deriving the first order conditions for I_K, I_D, C ,K, B, P, D from (A1) and excluding the dual variables, we obtain the following nonlinear system for possible *interior* optimal trajectories K, B, C, D and P :

$$AK^\alpha = \delta K + K' + \delta D + D' + B + C, \quad \text{(A2)}$$

$$\alpha AK^{\alpha-1} - \alpha\frac{B}{K} - \frac{C'}{C} = \delta + \rho, \quad \text{(A3)}$$

$$P' + \delta_P P = \gamma\left(\frac{AK^\alpha}{B} + Z\right), \quad \text{(A4)}$$

$$\eta(D)P^\mu = \frac{B}{\gamma AK^\alpha C}\left(B(\delta_P + \rho) + \alpha\frac{B}{K}K' + \frac{B}{C}C' - 2B'\right), \quad \text{(A5)}$$

$$-\eta'(D)\frac{P^{\mu+1}}{\mu+1} = \frac{1}{C}\left[\rho + \delta + \frac{C'}{C}\right]. \quad \text{(A6)}$$

Next, we analyze possible steady states of the problem under study. By (A2)-(A6), any positive constant (stationary) state ($\bar{K}$, $\bar{B}$, $\bar{C}$, $\bar{D}$, $\bar{P}$) of the problem (1)-(6), if it exists, should satisfy the following system of nonlinear equations:

$$A\bar{K}^\alpha = \bar{B} + \bar{C} + \delta\bar{K} + \delta\bar{D}, \quad \text{(A7)}$$

$$\alpha A\bar{K}^{\alpha-1} - \alpha\frac{\bar{B}}{\bar{K}} = \delta + \rho, \quad \text{(A8)}$$

$$\delta_P\bar{P} = \gamma(\frac{A\bar{K}^\alpha}{\bar{B}} + Z), \quad \text{(A9)}$$

$$[\underline{\eta} + (\bar{\eta} - \underline{\eta})e^{-a\bar{D}}]\bar{P}^\mu = \frac{\bar{B}^2}{\gamma A\bar{K}^\alpha\bar{C}}(\delta_P + \rho), \quad \text{(A10)}$$

$$\frac{\overline{P}^{\mu+1}}{\mu+1} a(\overline{\eta}-\underline{\eta})e^{-a\overline{D}} = \frac{\rho+\delta}{\overline{C}}. \tag{A11}$$

The rest of the proof follows (Yatsenko el al 2014). Lemma is proven.

Proofof Proposition 1 extends the analysis of Brechet et al (2013) for $Z = 0$ and includes similar steps. Namely, substituting (15) into (14), we get the equation (17). Next, introducing the dimensionless unknown variable $x = \frac{\rho}{\alpha A}\overline{K}^{1-\alpha}$, $0 < x < 1$, and the parameters

$$\kappa_{\min} = \frac{\eta_{\min}\gamma^{1+\mu}}{(\delta_P+\rho)\delta_P{}^{\mu}}, \qquad \kappa_{\max} = \frac{\eta_{\max}\gamma^{1+\mu}}{(\delta_P+\rho)\delta_P{}^{\mu}}, \tag{A12}$$

we obtain from (17) the equation

$$\frac{(1-x)^{2+\mu}}{x} = \kappa_{\min}\left[1+Z(1-x)\right]^{\mu} + \frac{\alpha\delta_P(\mu+1)}{a(\delta_P+\rho)(\alpha A/\rho)^{\frac{1}{1-\alpha}}}\frac{(1-x)^{1+\mu}}{x^{\frac{1}{1-\alpha}}\left[1+Z(1-x)\right]^{\mu}} \tag{A13}$$

The left-hand side $F(x) = \frac{(1-x)^{2+\mu}}{x}$ of equation (A13) strictly decreases from ∞ at $x = 0$ to $F(1) = 0$ and is the same as in the case $Z = 0$. The right-hand function

$$G(x) = \kappa_{\min}\left[1+Z(1-x)\right]^{\mu} + \frac{\alpha\delta_P(\mu+1)}{a(\delta_P+\rho)(\alpha A/\rho)^{\frac{1}{1-\alpha}}}\frac{(1-x)^{1+\mu}}{x^{\frac{1}{1-\alpha}}\left[1+Z(1-x)\right]^{\mu}}$$

strictly decreases from ∞ at $x = 0$ to $\kappa_{\min}$ at $x = 1$ (exactly as at $Z = 0$).

Similarly to (Brechet et al 2013), now we can prove that, if $D\left((\alpha A\hat{x}/\rho)^{1/(1-\alpha)}\right) > 0$, where $\hat{x}$ is the solution of the equation

$$\frac{(1-\hat{x})^{2+\mu}}{\hat{x}} = \kappa_{\min}[1+Z(1-\hat{x})]^{1+\mu}, \tag{A14}$$

then the functions $F(x)$ and $G(x)$ intersect at a unique point x^*, $\hat{x} < x^* < 1$, and, therefore, the equation (A13) has a unique solution. The proposition is proven.

Proof of Proposition 2. The case of a small κ-indicator ($\kappa_{\max} << 1$) is obvious. Let us focus on the case (20) when the κ-indicator is high. Then, the dimensionless unknown $x = \frac{\rho}{\alpha A}\overline{K}^{1-\alpha}$, introduced in the proof of Proposition 1 is small: $0 < x << 1$. Correspondingly, by (8) and (9),

$$\overline{C} = \overline{K}\rho/\alpha, \qquad \overline{B} = A\overline{K}^{\alpha}(1-\overline{K}^{1-\alpha}\rho/(\alpha A)) \approx A\overline{K}^{\alpha}.$$

Finally, $\overline{D}(\overline{K})$ is defined by (15). Assuming (20) and substituting (21) into (15), we obtain that $\overline{D}(Z) \sim \ln\left\{\left[(1+Z)^{-\mu}\right]^{\frac{1}{1-\alpha}}(1+Z)^{\mu+1}\right\}$. So, $\overline{D}$ increases in Z when $\mu < (1-\alpha)/\alpha$. This completes the proposition proof.

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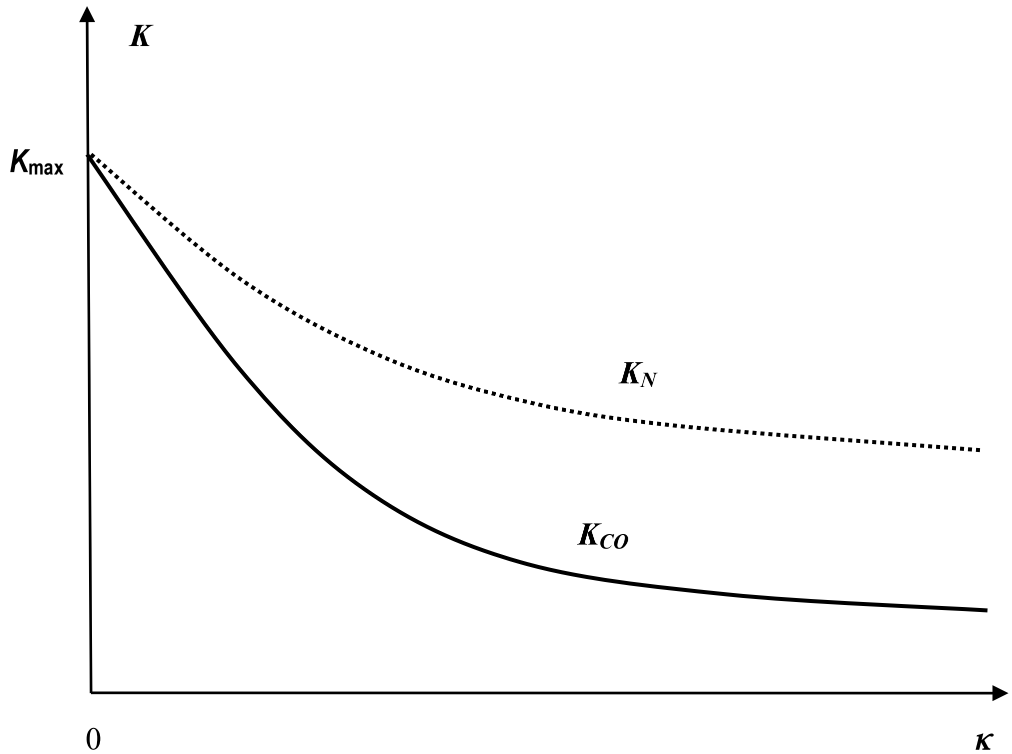

Figure 1. The dependence of the optimal economy size K on the environmental vulnerability indicator κ in the competitive OLNE case (dotted curve K_N) and the cooperative case (solid curve K_{CO}). The size is the same $\overline{K}_{\max} = (\alpha A / \rho)^{1/(1-\alpha)}$ at $\kappa = 0$. The ratio K_N / K_{CO} approaches $2^{1/(1-\alpha)}$ when κ increases and becomes large.

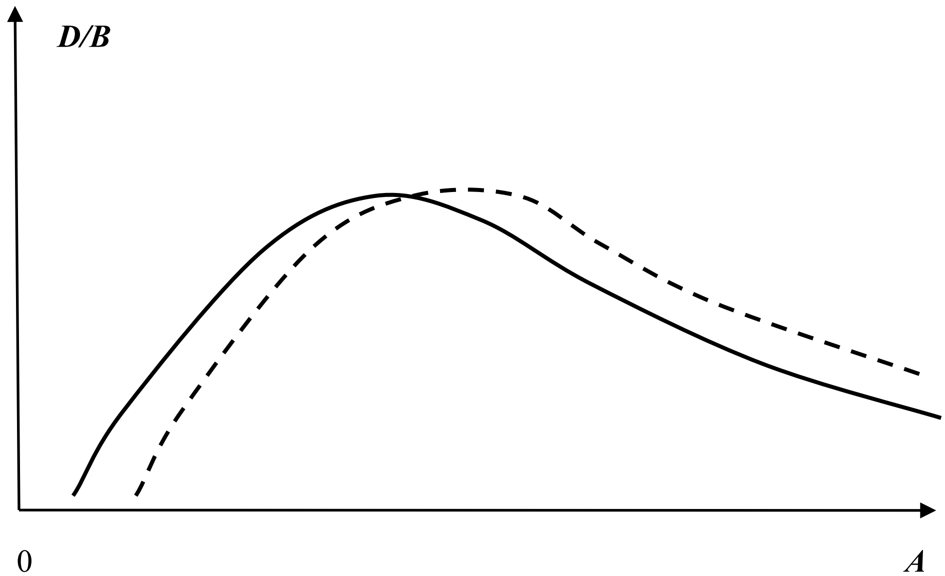

Figure 2. The dependence of the optimal adaptation–mitigation ratio *D/B* on the country productivity *A* in the competitive OLNE case (solid curve) and the cooperative case (dashed curve).

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