Adaptation to Climate Change: Commitment and Timing Issues

March 16, 2017

Abstract

We study the impact of timing and commitment on adaptation and mitigation policies in the context of international environmental problems. Adaptation policies present the characteristics of a private good and may require a prior investment, while mitigation policies produce a public good. In a stylized model, we evaluate the impact of strategic commitment and leadership considerations when countries with different attitudes towards environmental cooperation coexist. We obtain equilibrium abatement and adaptation levels and environmental costs under partial cooperation for various timing and leadership scenarios. Crucially, global environmental costs suffered by countries are found to be greater when adaptation measures can be used strategically.

Keywords: Adaptation, Climate change, Leadership, Mitigation, Strategy, Timing.

1 Introduction

One of the consequences of climate change is the increasing frequency of extreme weather events occurring around the globe. Unusually high rainfall is becoming a significant cause of floods, as for example in 2013 in Alberta (Canada) and in Germany, Austria, the Czech

Republic and France. On the other hand, droughts are becoming longer, harsher and more frequent, as experienced for instance in 2012 in many U.S. states and in Russia, England and Wales.

To limit climate change, it has been suggested that countries need both to reduce their greenhouse gas (GHG) emissions substantially and sustainably, and to invest in adaptive measures (see the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (2014), the European Commission Climate Action (2015), and President Barack Obama's 2013 Climate Action Plan). Mitigation policies consist of any means to cut down GHG emissions, from reducing deforestation and investing in new clean technologies and renewable energies, to changing consumer behavior; their aim is to prevent the adverse consequences of climate change by reducing its rate and magnitude. Mitigation policies find their roots in the 1992 United Nations Framework Convention on Climate Change and in all the ensuing UN Climate Change Conferences. However, the effectiveness of mitigation policies is limited by two factors. The first one, called *climate inertia*, is intrinsic to the climate system itself. Climate inertia refers to the long period required to reach a new climate system equilibrium after the stabilization of the atmospheric concentration of CO2 and other greenhouse gases. The second factor is related to the relatively small number of countries committed to GHG emissions reduction, and to the limited extent of their reductions. On the other hand, adaptation policies are designed to alleviate the damages if the adverse consequences of climate change (floods, droughts, heat waves) should materialize. Adaptation policies can take many different forms, such as early warning systems, sea walls, flood levees, irrigation systems, or the development of new crop varieties adapted to drought or changes in temperature.

Although adaptation and mitigation policies are both answers to the risks of climate change, they show some important differences. The first one is the time scale of their impact: while adaptation has the potential to reduce the risks of climate change over the next few decades, mitigation has relatively little influence on climate outcomes over this time

scale. The second difference lies in the nature of the investment, where adaptation shows all the characteristics of a private good (with costs and benefits sustained and enjoyed by the individual country that adopts it), while mitigation presents all the features of a public good, including the risk of free-riding.

In line with the IPCC Fifth assessment report statement that "adaptation and mitigation are complementary strategies for reducing and managing the risks of climate change" (IPCC (2014), page 76), in this paper, we study countries' decisions about adaptation and mitigation expenditures, under different assumptions on commitment and timing. In particular, we consider the cases where investments in adaptation measures can be made prior to or simultaneously with mitigation decisions, and the cases where a group of countries can take leadership in environmental measures by making prior commitments.

The literature on adaptation (or self-protection) and mitigation (or abatement) has developed in several directions.[1] A first group of papers analyzes the relationship between adaptation and mitigation policies, that is, whether and when they are substitutes or complements (see, e.g., Yohe and Strzepek (2007), Lecocq and Shalizi (2007), and Ingham et al. (2013)). Other authors focus on how the introduction of adaptive measures against climate change affects the stable size of international environmental agreements (IEA) aimed at reducing GHG emissions (see, e.g., Barrett (2008), Marrouch and Chaudhuri (2011) and Buob and Siegenthaler (2011)). A third stream of the literature studies the optimal mix of mitigation and adaptation policies as responses to the effects of climate change (see, e.g., Kane and Shogren (2000), Tulkens and van Steenberghe (2009), Bréchet et al. (2013) and Farnham and Kennedy (2014)).

Some of these topics have been further developed by explicitly including the timing of decisions in the problem setting. Papers that clearly mention the timing of investments in both types of environmental policies and their strategic interactions include De Bruin et al. (2011), where the level of adaptation is chosen before solving the emissions game in

[1] For a recent survey please refer to Agrawala et al. (2011).

the context of evaluating coalition structures in IEA; Buob and Stephan (2011) and Ebert and Welsch (2012), where adaptation is timed after mitigation in the context of determining the optimal mix between the two types of investments; Eisenack and Kähler (2012), who add a leadership structure to the setting of Ebert and Welsch (2012); and Zehaie (2009), who considers three different sequences[2] in the context of analyzing the impact of different strategic commitments to adaptation.

By focusing on the consequences of the timing of adaptive investments with respect to mitigation decisions, our paper is close in spirit to the one by Zehaie (2009), as we share a similar research question. However, our setting allows the interaction of cooperators with non-cooperators (or partial cooperation), which is not possible in a two player model, where either both players cooperate, or none does. In addition, by specifying functional forms, we are able to evaluate the consequences of strategic timing on welfare, at both the global and the individual level. Note that papers that do allow for partial cooperation, namely in the context of IEA stability issues, do not consider the possibility of different timing and commitment scenarios.

The aim of our paper is to study the consequences of different strategic commitments to adaptive investments as a complementary strategy to mitigation policies, when countries have different attitudes as a response to climate change. In order to do this, we develop a multiple country model where agents minimize their environmental cost by choosing their adaptation and mitigation levels, and where a subset of countries, of arbitrary size, cooperate in order to reduce their joint costs. We consider two types of adaptive investments: the ones that require some prior commitment (e.g. major investments such as dykes), and the ones that can be carried out simultaneously with mitigation decisions (e.g. use of more resistant crop varieties). Furthermore, we examine the case where these cooperating countries become leaders in environmental policies while the other (individualistic) countries act as followers. This allows us to contribute to the existing literature in three different ways. Firstly, we

[2]Namely, the decision about the adaptation level is made before, after and simultaneously with the mitigation one, where the last two sequences are shown to be equivalent.

extend the results on strategic interactions observed in two-country models to a more general setting with n-countries. Secondly, we derive new strategic interactions arising in the context of partial cooperation, that is, among players with different attitudes toward cooperation, and with different leadership positions. Finally, we perform a complete comparison, not only between different timing of adaptive investments but also between different coexisting behaviors, for all the variables involved in the problem (i.e. environmental costs, adaptation and mitigation levels).

The main results of our paper are the following: regardless of the number of cooperating countries, a greater environmental cost is suffered when countries commit to investments in adaptive measures before they decide about mitigation measures. When adaptation investments are made before the mitigation decisions, countries can take advantage of a strategic effect and increase adaptation to reduce their mitigation effort, which is shown to be globally inefficient. Finally, leadership in responding to the effects of climate change is not beneficial from an aggregate point of view, but it is convenient for the countries that become leaders.

The rest of the paper is organized as follows. Section 2 describes the model; Section 3 computes the equilibrium levels of all variables for the two types of adaptive investments; prior (Section 3.1) and concurrent (Section 3.2) adaptation. Section 4 performs the same analysis for the case where cooperating countries take the leadership in responding to climate change effects. Section 5 compares equilibrium solutions under various settings, and Section 6 draws the main conclusions. Proofs are provided in the Appendix.

2 The model

We consider n symmetric countries, each of which produces an economic output denoted by o_j. The production activity carried out by a country, in addition to generating economic value, creates emissions according to the relationship $e_j = \alpha_j o_j$, where α_j is a parameter related to the cleanliness of the production technologies used by country j. We normalize

$\alpha_j o_j = 1$ for each j, so that the optimal emissions of each country when there is no environmental concern is equal to 1. Pollution reduces the welfare (e.g., losses in productivity) of each country, and this reduction is increasing in total GHG emissions, denoted by E.

Countries can respond to the effects of climate change caused by pollution with two different environmental policies. The first one is called *adaptation* and it consists of investing in some form of private measures to counteract the consequences of climate change (dams, diversion canals, irrigation, crop diversification). This policy reduces the country's vulnerability to pollution but does not change the pollution level, so that each country's environmental vulnerability is given by

$$v_j = E - b_j$$

where $b_j \in [0, E]$ measures the reduction in vulnerability resulting from adaptive measures. The cost of adaptation for country j is an increasing convex function of b_j, assumed quadratic, that is,

$$\mathcal{A}_j(b_j) = \frac{\gamma_A}{2} b_j^2$$

where $\gamma_A > 0$ is the adaptation cost coefficient.

The second environmental policy is called *mitigation* and it consists of any means aimed at curtailing a country's GHG emissions e_j (filters, catalytic converters, expanded forests, etc.). Mitigation is represented by the variable

$$m_j = 1 - e_j$$

where $m_j \in [0, 1]$ is the reduction in the country's emissions with respect to the base level of 1. The cost of mitigation for country j is an increasing convex function of m_j, assumed quadratic, that is,

$$\mathcal{M}_j(m_j) = \frac{\gamma_M}{2} m_j^2$$

where $\gamma_M > 0$ is the mitigation cost coefficient.

Contrary to self-protective adaptation measures, mitigation has the characteristics of a public good, so that the total pollution from all countries is given by

$$E = \sum_{j=1}^{n} (1 - m_j) .$$

The overall environmental cost for a representative country j is thus given by

$$z_j = \frac{\gamma_E}{2} (E - b_j)^2 + \frac{\gamma_M}{2} m_j^2 + \frac{\gamma_A}{2} b_j^2 \tag{1}$$

where $\mathcal{D}_j(E, b_j) = \frac{\gamma_E}{2} (E - b_j)^2$ is the monetized value of the environmental damage, increasing and convex in environmental vulnerability, and $\gamma_E > 0$ is the environmental sensitivity coefficient. The objective of a country j is to choose the mitigation and adaptation levels that minimize the environmental cost z_j.

Note that our stylized model includes the three sources of costs commonly used in the climate change literature, as reported in Tulkens and van Steenberghe (2009): mitigation (m), adaptation (b) and suffering ($v = E - b$). Moreover, it is consistent with the usual assumptions about the behavior of these costs:

$$\begin{array}{lll} \mathcal{A}_j' > 0 & \mathcal{M}_j' < 0 & \frac{\partial}{\partial E}\mathcal{D}_j > 0, \frac{\partial}{\partial b_j}\mathcal{D}_j < 0 \\ \mathcal{A}_j'' \geq 0 & \mathcal{M}_j'' \geq 0 & \frac{\partial^2}{\partial E^2}\mathcal{D}_j > 0, \frac{\partial^2}{\partial b_j^2}\mathcal{D}_j \geq 0 \\ & & \frac{\partial^2}{\partial E \partial b_j}\mathcal{D}_j = \frac{\partial^2}{\partial b_j \partial E}\mathcal{D}_j \leq 0, \end{array} \tag{2}$$

as in e.g. Tulkens and van Steenberghe (2009), Zehaie (2009), Ebert and Welsch (2012), Eisenack and Kähler (2012), and Ingham et al. (2013).[3]

Note that a numeraire can be chosen so that $\gamma_M = 1$ and the total environmental cost is

[3] Other papers adopting stylized functional forms in the literature use slightly different assumptions. The model of Buob and Stephan (2011) is consistent with (2), but uses a Cobb-Douglas formulation for the players' utility. On the other hand, both Farnham and Kennedy (2015) and Marrouch and Ray Chauduri (2011) assume that the damage cost is bi-linear, which requires additionnal conditions on parameter values to ensure that the optimization problems are convex and that marginal costs have the expected signs.

expressed in terms of the mitigation cost coefficient. In this numeraire, the environmental sensitivity parameter is $\omega \equiv \frac{\gamma_E}{\gamma_M} > 0$. We then use the change of variable $a_j = \omega b_j$ for the adaptation decision variable, where a_j is the level of *effective adaptation*, and the cost function for a representative country j can then be equivalently expressed, using only two parameters, as

$$c_j = \frac{\omega}{2}E^2 - Ea_j + \frac{1}{2}m_j^2 + \frac{\theta}{2}a_j^2 \tag{3}$$

where $\theta \equiv \gamma_M \frac{\gamma_A + \gamma_E}{\gamma_E^2} > 0$ is a parameter accounting for the impact of adaptive measures on both the adaptation and environmental costs.

The optimization problem for country j is then

$$\min_{m_j, a_j} \left\{ c_j = \frac{\omega}{2}E^2 - Ea_j + \frac{1}{2}m_j^2 + \frac{\theta}{2}a_j^2 \right\} \tag{4}$$

with

$$E = \sum_{j=1}^{n} (1 - m_j) = n - m_j - \sum_{k \neq j} m_k. \tag{5}$$

Note that $\theta\omega = \frac{\gamma_A + \gamma_E}{\gamma_E} > 1$, which ensures that the cost function of an individual country, given the environmental strategies of the other countries, is strictly convex. Notice also that the restriction $b_j \leq E$ is always satisfied in equilibrium; if it were not the case, a player could deviate by choosing $b_j' = E < b_j$, thus reducing both his environmental and adaptation costs without changing his mitigation cost.

Although countries are symmetric with respect to their baseline output and cost parameters, we assume that they do not have the same attitude towards the issue of climate change. Indeed, we distinguish between two groups of countries. In the first group, countries agree to coordinate their environmental policies by minimizing their joint total environmental cost, and we call them *cooperating* countries. Cooperating countries jointly decide on both adaptation and mitigation levels.[4] The second group is made up of countries that establish their

[4] The alternative assumption that cooperating countries choose their mitigation levels jointly and their investment in adaptive measures individually is called *semi-cooperation* in Zehaie (2009).

environmental policies by minimizing their own individual overall environmental cost, and we call them *individualistic* countries. In the sequel, variables pertaining to cooperating countries are indexed by C, while those pertaining to individualistic countries are indexed by I. The proportion of cooperating countries is given by p, and the proportion of individualistic countries is denoted by $q \equiv 1 - p$. The proportion of cooperating countries is exogenously given and their attitude could be the result of a self-enforcing agreement, or of any additional features favouring cooperation (e.g. issue linkage, transfers, political reasons, reputation effects, etc.).

The optimization problem (4)-(5) will be used to compute mitigation and adaptation levels, both expressed in the form of either reaction functions or equilibrium solutions. To explicitly distinguish between these various forms, we emphasize reaction functions with a tilde, e.g. $\tilde{m}_{Ij}^{K}(\cdot)$ is the mitigation level of individualistic country j in scenario K as a function of the decisions taken by the other players, and equilibrium solutions with a hat or a bar, e.g. $\bar{m}_{C}^{K}(\cdot)$ is the equilibrium mitigation strategy in scenario K of cooperating countries resulting from adaptation decisions taken in a previous stage. Global equilibrium solutions are unaccented.

To compute the equilibrium solutions, we assume that each player's decisions are interior. The set of parameter values generating interior solutions depends on the number of players of each type. Notice that the condition

$$\gamma_M \left(\frac{1}{\gamma_A} + \frac{1}{\gamma_E} \right) > \frac{1}{4} (n-1)^2$$

ensures that solutions are interior for any proportion of cooperating countries, and for all the scenarios analyzed in the following. This condition amounts to requiring that mitigation costs are high enough with respect to adaptation and environmental costs.

3 Types of adaptation

In order to address the strategic role of timing and commitment to environmental policies, we consider in this section two different assumptions about the sequence of decisions made by countries. Under the first assumption, countries commit to self-protective adaptation measures before deciding on their mitigation levels; this commitment may be taken for strategic reasons, or may be due to the fact that adaptation requires a prior investment. Under the second assumption, there is no prior commitment by countries to adaptation, which then plays no strategic role since it results in a private good.

3.1 Adaptation as a prior investment

We first analyze the situation in which adaptation requires a prior investment, and mitigation decisions are dependent on adaptation choices that have been committed to by players. This is modelled as a two-stage game solved by backward induction.

3.1.1 Interaction between the two types of countries

Results pertaining to the prior investment case with partial cooperation are indexed by the superscript PN. Starting from the second stage mitigation game, a representative cooperating country j solves

$$\min_{m_C} \left\{ c_{Cj} = \frac{\omega}{2} \left(n - npm_C - M_I\right)^2 - \left(n - npm_C - M_I\right) a_{C_j} + \frac{1}{2} m_C^2 + \frac{\theta}{2} a_{C_j}^2 \right\}$$

where M_I denotes the total mitigation effort of individualistic players and a_{C_j} is the adaptation decision of cooperating country j. From the first-order condition we derive the mitigation reaction function

$$\tilde{m}_C^{PN}\left(M_I, A_C\right) = \frac{n^2 p\omega - np\omega M_I - A_C}{n^2 p^2 \omega + 1}, \tag{6}$$

common to cooperating countries, where A_C denotes the total adaptation level of all cooperating countries. Note that in deriving (6), we do not assume that the adaptation effort is identical across cooperating countries, and therefore the reaction function represents the best joint response to any outcome of the first stage adaptation game, not necessarily in equilibrium. The mitigation reaction function (6) is negatively sloped with respect to the individualistic players' level of mitigation, which means that if the global mitigation level of individualistic countries increases, cooperating countries will respond by reducing theirs, that is, the curtailing of emissions are strategic substitutes between the two types of countries. The impact of M_I is increasing in the the environmental sensitivity parameter ω. The mitigation reaction of cooperating countries (6) is also negatively affected by their total adaptation expenditures, showing that adaptation and mitigation are strategic substitutes for cooperating countries: clearly, the greater are their expenditures in adaptation, the less vulnerable to climate change the countries become and the less they will mitigate. The impact of A_C is decreasing in the environmental sensitivity.

For a representative individualistic country j, the optimization problem to solve is given by

$$\min_{m_{Ij}} \left\{ c_{Ij} = \frac{\omega}{2} \left(n - m_{Ij} - M_C - M_{I-j}\right)^2 - \left(n - m_{Ij} - M_C - M_{I-j}\right) a_{Ij} + \frac{1}{2} m_{Ij}^2 + \frac{\theta}{2} a_{Ij}^2 \right\}$$

where M_{I-j} denotes the total mitigation effort by the other individualistic countries and $M_C = npm_C$ is the total mitigation effort by the cooperating countries. The corresponding reaction function is given by

$$\tilde{m}_{Ij}^{PN}\left(M_{I-j}, M_C, a_{I_j}\right) = \frac{\omega\left(n - M_{I-j} - M_C\right) - a_{Ij}}{\omega + 1}. \tag{7}$$

This reaction function presents the same characteristics as (6): an individualistic country's mitigation is negatively related to other players' mitigation and to its own adaptation. Simultaneously solving (7) for all individualistic countries yields their equilibrium reaction to

the mitigation decisions of cooperating countries and to the adaptation decisions made in the first stage:

$$\hat{m}_{Ij}^{PN}\left(M_C, A_{I-j}, a_{I_j}\right) = \frac{\omega\left(n - M_C + A_{I-j}\right) - \left(\omega\left(nq-1\right)+1\right)a_{Ij}}{nq\omega+1} \tag{8}$$

where a_{Ij} is the adaptation decision of individualistic country j, and A_{I-j} denotes the total adaptation by the other individualistic countries. As before, this mitigation reaction function is derived without assuming that individualistic countries' adaptation levels are equal.

The solution of the second-stage mitigation game is the subgame-perfect Nash equilibrium given by the simultaneous solution of the reaction functions, that is:

$$\bar{m}_C^{PN}\left(A_C, A_I\right) = \frac{n^2p\omega - \left(nq\omega+1\right)A_C + np\omega A_I}{n^2p^2\omega + nq\omega + 1} \tag{9}$$

$$\bar{m}_{Ij}^{PN}\left(A_C, A_I, a_{Ij}\right) = \omega\frac{n + npA_C + A_I}{n^2p^2\omega + nq\omega + 1} - a_{Ij} \tag{10}$$

where A_I is the total adaptation by individualistic countries. Note that the equilibrium mitigation decisions depend on the investment in adaptation measures from both types of countries. For cooperating countries, mitigation is a strategic complement to the adaptive policies of individualistic countries, and a strategic substitute to their joint adaptive actions. For individualistic countries, mitigation is a strategic complement to the adaptive policies of all other countries, and strategic substitute to their own adaptation level. For example, if cooperating countries jointly increase their investment in adaptive measures, this allows them to decrease their mitigation effort, as they become less vulnerable to the negative impact of pollution. The same increase in adaptive measures makes the individualists' mitigation task more difficult, as an increase in emissions from cooperating countries hurts the individualistic countries, which are forced to give a stronger response in terms of emissions reduction. In the same way, when an individualistic country unilaterally increases its adaptation investment, this leads to a decrease in the mitigation effort of that country and to an increase in the mitigation effort of all the others. This shows how both types of countries, by choosing

their adaptive measures in the first stage, can strategically affect the result of the mitigation game.

The total emissions for the subgame-perfect Nash equilibrium are given by

$$\bar{E}^{PN}\left(A_C, A_I\right) = \frac{n + npA_C + A_I}{n^2p^2\omega + nq\omega + 1}, \tag{11}$$

where it is apparent that an increase in adaptive measures against climate change leads to an increase in total emissions. Notice that total emissions are negatively related to the environmental sensitivity parameter ω.

In the first stage, players take into account the Nash equilibrium solutions (9), (10), (11), and a representative cooperating country computes its investment in adaptation by solving

$$\min_{a_C}\left\{c_{C_j} = \frac{\omega}{2}\left(\bar{E}^{PN}\left(npa_C, A_I\right)\right)^2 - \left(\bar{E}^{PN}\left(npa_C, A_I\right)\right)a_C + \frac{1}{2}\left(\bar{m}_C^{PN}\left(npa_C, A_I\right)\right)^2 + \frac{\theta}{2}a_C^2\right\},$$

where $A_C = npa_C$ results from symmetry and from the assumption that cooperating country coordinate their adaptation policies. From the first-order condition, using

$$X \equiv n^2p^2\omega \tag{12}$$

$$Y \equiv nq\omega \tag{13}$$

$$W \equiv X + Y + 1, \tag{14}$$

we derive the reaction function

$$\tilde{a}_C^{PN}\left(A_I\right) = \frac{\left(X+1\right)\left(Y+1\right)\left(A_I+n\right)}{\theta W^2 - n^2p^2\left(X - Y^2 + 1\right)}, \tag{15}$$

which is positively related to the adaptation effort of individualistic countries, meaning that preventive actions taken by the countries against the impact of climate change are strategic complements.

A representative individualistic country j chooses its adaptation level by solving

$$\min_{a_{Ij}} \left\{ c_{Ij} = \frac{\omega}{2} \left(\bar{E}^{PN} \left(A_C, A_{I-j} + a_{Ij} \right) \right)^2 - \left(\bar{E}^{PN} \left(A_C, A_{I-j} + a_{Ij} \right) \right) a_{Ij} \right.$$
$$\left. + \frac{1}{2} \left(\bar{m}_{Ij}^{PN} \left(A_C, A_{I-j} + a_{Ij}, a_{Ij} \right) \right)^2 + \frac{\theta}{2} a_{Ij}^2 \right\}.$$

From the first-order conditions, we find a similar complementarity in the reaction of individualistic countries to the adaptation commitment of other countries, that is,

$$\tilde{a}_I^{PN} \left(A_C, A_{I-j} \right) = (\omega + 1)(W - \omega) \frac{n + npA_C + A_{I-j}}{\theta W^2 + (W - \omega - 1)^2 - \omega - 1}$$

and in the individualistic countries equilibrium reaction to the adaptation commitment of cooperating countries:

$$\hat{a}_I^{PN} \left(A_C \right) = \frac{n(\omega + 1)(pA_C + 1)(W - \omega)}{\theta W^2 + (W - \omega - 1)(X + 1) - nqW}. \tag{16}$$

The solution of the system (15)-(16) gives the equilibrium solution of the whole game:

$$\begin{aligned}
a_C^{PN} &= n \frac{\omega^2 (Y + 1)(X + 1)(X + Y - \omega + \theta W)}{K_1} \\
a_I^{PN} &= n \frac{\omega (\omega + 1)(W - \omega)(\theta \omega W + XY)}{K_1} \\
m_C^{PN} &= n^2 p \omega^2 W (\theta \omega - 1) \frac{X + Y - \omega + \theta W}{K_1} \\
m_I^{PN} &= n \omega W (\theta \omega - 1) \frac{XY + \theta \omega W}{K_1}
\end{aligned}$$

where

$$\begin{aligned}
K_1 &= W^3 (\theta \omega - 1)^2 + W (Y + 1)(X + 1) \\
&\quad + (\theta \omega - 1) W (X + 1) \left(X + 3Y + Y^2 + 2 \right) \\
&\quad + \omega (X + 1)(X + Y - \omega)((\theta \omega - 1) W + Y + 1).
\end{aligned}$$

Claim 1 *When the two types of countries interact and adaptive measures are a prior investment with respect to mitigation decisions, a cooperating country always adapts more than a individualistic country, and suffers a greater environmental cost. When there are more individualistic countries than cooperating countries, for θ small enough, the mitigation level of cooperating countries is lower than that of individualistic countries.*

It is interesting to note that the mitigation level of cooperating countries can be lower than that of individualistic countries, contrary to the usual result in partial cooperation mitigation games. Nonetheless, cooperating countries still suffer a greater cost than individualistic countries.

To conclude, when adaptation is a prior investment, its impact on subsequent mitigation decisions, (see Equations (9)-(10)) gives adaptation policies a strategic role, even though adaptation is a private good.[5]

3.1.2 Singular type special cases

If we consider the special cases where all players are of the same type, we obtain a generalization of the results found in Zehaie (2009) to the n player case.

The first best solution is obtained by setting $p = 1$ (all players are cooperators). In this case, the timing of decisions does not matter and adaptation has no strategic role, as all countries solve a joint optimization problem. This solution is indexed by the superscript FB and is given by

$$\begin{aligned} a^{FB} &= \frac{n}{K_2} \\ m^{FB} &= n^2 \frac{\theta\omega - 1}{K_2} \\ \text{where } K_2 &= \theta + n^2 (\theta\omega - 1) . \end{aligned}$$

[5] Notice that, because of this strategic role, the equilibrium results would be different if cooperators agreed to coordinate only their mitigation policies (semi-cooperation).

By using $a^{FB} = \omega b^{FB}$, we find that $\gamma_M m^{FB} = n\gamma_A b^{FB}$. As noted in Zehaie (2009), in the first best solution, mitigation is preferred to adaptation because of its public good characteristics.

The non-cooperative solution with prior commitment is obtained by setting $q = 1$ (all players are individualists). This scenario is indexed by the superscript PI and generalizes the first non-cooperative case studied in Zehaie (2009) ("self-protection before abatement"). As in Zehaie (2009), we find that mitigation levels are strategic substitutes between players and, for a given player, adaptation is a strategic substitute to mitigation:

$$\tilde{m}_{Ij}^{PI}\left(M_{I-j}, a_{I_j}\right) = \frac{\omega\left(n - M_{I-j}\right) - a_{Ij}}{\omega + 1}.$$

With n players, we find the additional result that the equilibrium mitigation level is positively related other players' adaptation, and negatively related to own adaptation, and that adaptation levels are strategic complements between players:

$$\bar{m}_{Ij}^{PI}\left(A_{I-j}, a_{Ij}\right) = \frac{n\omega + \omega A_{I-j} - a_{Ij}\left(\omega\left(n-1\right)+1\right)}{n\omega + 1}.$$

$$\tilde{a}_{I}^{PI}\left(A_{I-j}\right) = \left(\omega+1\right)\left(\omega\left(n-1\right)+1\right)\frac{n + A_{I-j}}{\theta\left(n\omega+1\right)^2 + \omega^2\left(n-1\right)^2 - \omega - 1}.$$

The equilibrium solution to the n-player non-cooperative game is given by

$$\begin{aligned} a^{PI} &= \frac{n\left(\omega+1\right)\left(-\omega + n\omega + 1\right)}{K_3} \\ m^{PI} &= \frac{n\left(\theta\omega - 1\right)\left(n\omega + 1\right)}{K_3} \\ \text{where } K_3 &= \theta\left(n\omega+1\right)^2 - n\omega\left(n-1\right) - \omega - n. \end{aligned}$$

3.2 Adaptation as a concurrent investment

We now study the case where adaptation and mitigation decisions are made concurrently by the players.

3.2.1 Two types of players

Results pertaining to the simultaneous investment case with partial cooperation are indexed by the superscript SN. When decisions are made concurrently, a representative cooperator solves

$$\min_{m_C, a_C} \left\{ c_{Cj} = \frac{\omega}{2} \left(n - npm_C - M_I \right)^2 - \left(n - npm_C - M_I \right) a_C + \frac{1}{2} m_C^2 + \frac{\theta}{2} a_C^2 \right\}$$

yielding the first-order conditions

$$\begin{cases} m_C = \frac{n^2 p \omega}{n^2 p^2 \omega + 1} - \frac{np\omega}{n^2 p^2 \omega + 1} M_I - \frac{np}{n^2 p^2 \omega + 1} a_C \\ a_C = \frac{n - npm_C - M_I}{\theta}. \end{cases}$$

By solving the FOCs above we derive the reaction functions of cooperating countries as

$$\begin{aligned} \tilde{m}_C^{SN} \left(M_I \right) &= \frac{np \left(\theta\omega - 1 \right) \left(n - M_I \right)}{\theta + n^2 p^2 \left(\theta\omega - 1 \right)} \\ \tilde{a}_C^{SN} \left(M_I \right) &= \frac{n - M_I}{\theta + n^2 p^2 \left(\theta\omega - 1 \right)}. \end{aligned}$$

A representative individualistic country solves the optimization problem

$$\min_{m_{Ij}, a_{Ij}} \left\{ c_{I_j} = \frac{\omega}{2} \left(n - m_{Ij} - M_C - M_{I-j} \right)^2 - \left(n - m_{Ij} - M_C - M_{I-j} \right) a_{Ij} + \frac{1}{2} m_{Ij}^2 + \frac{\theta}{2} a_{Ij}^2 \right\} \tag{17}$$

with first-order conditions

$$\begin{cases} m_{Ij} = \frac{n\omega}{nq\omega + 1} - \frac{\omega}{nq\omega + 1} M_C - \frac{1}{nq\omega + 1} a_{Ij} \\ a_{Ij} = \frac{n - M_C - M_I}{\theta}. \end{cases}$$

The reaction functions are then

$$\begin{aligned}
\tilde{m}_I^{SN}(M_C) &= (n - M_C)\frac{\theta\omega - 1}{\theta + nq(\theta\omega - 1)} \\
\tilde{a}_I^{SN}(M_C) &= \frac{n - M_C}{\theta + nq(\theta\omega - 1)}.
\end{aligned}$$

By examining the reaction functions of both types of countries, we find that adaptation decisions no longer play any strategic role, but, as in the prior-commitment case, mitigation decisions by the two types of countries are strategic substitutes, and adaptation decisions are strategic substitutes to the mitigation decisions of the other-type players.

The solution of the whole game is then given by

$$\begin{aligned}
a_C^{SN} &= a_I^{SN} = \frac{n}{K_4} \\
m_C^{SN} &= \frac{n^2 p(\theta\omega - 1)}{K_4} \\
m_I^{SN} &= \frac{n(\theta\omega - 1)}{K_4} \\
\text{where } K_4 &= \theta + n\left(q + np^2\right)(\theta\omega - 1).
\end{aligned}$$

Claim 2 *When the two types of countries interact and adaptation and mitigation are established at the same time, cooperators and individualists allocate the same amount of resources to adaptation, which is proportional to the total emissions. Individualistic countries mitigate less and suffer a smaller environmental cost than cooperating countries.*

In the concurrent investments case, there is no strategic effect of adaptation policies between the two groups of countries. The equilibrium result is similar to what is usually observed in partial cooperation mitigation games: individualistic countries take advantage of the positive externality generated by cooperators and mitigate less, thus suffering a lower environmental cost.

3.2.2 Singular type special case

If we consider the special case where all players are individualistic, by setting $q = 1$ we generalize the second and third non-cooperative cases studied in Zehaie (2009) (self-protection simultaneous and after abatement, which are shown to be equivalent) to the n player case. This scenario is indexed by the superscript SI. The equilibrium solution among the non-cooperating players is then given by

$$\begin{aligned} a^{SI} &= \frac{n}{K_5} \\ m^{SI} &= \frac{n(\theta\omega - 1)}{K_5} \\ \text{where } K_5 &= \theta + n(\theta\omega - 1). \end{aligned}$$

As in Zehaie (2009), we find that $\gamma_M m^{FB} = \gamma_A b^{FB}$, that is, marginal costs of both environmental measures are equal at equilibrium.

4 Leadership in environmental policies

We consider again the two types of adaptive investments but we now introduce the hypothesis that cooperating countries act as leaders in both mitigation and adaptation decisions while individualistic countries behave as followers. Results pertaining to the prior investment case with leadership are indexed by the superscript PL, while those pertaining to the simultaneous investment case with leadership are indexed by the superscript SL.

4.1 Adaptation as a prior investment

In this case we assume that countries commit to adaptation before mitigation, and that cooperating countries act as leaders, both for adaptation and mitigation decisions. We model this situation as a two-stage Stackelberg game and we solve it by backward induction

starting from the second stage, where a representative individualistic country chooses its mitigation level by minimizing

$$\min_{m_{Ij}} \left\{ c_{Ij} = \frac{\omega}{2} \left(n - m_{Ij} - M_C - M_{I-j} \right)^2 - \left(n - m_{Ij} - M_C - M_{I-j} \right) a_{Ij} + \frac{1}{2} m_{Ij}^2 + \frac{\theta}{2} a_{Ij}^2 \right\}.$$

As in Section 3.1, Equation (8), the equilibrium reaction function of individualistic counties is given by

$$\hat{m}_{Ij}^{PL} \left(M_C, A_{I-j}, a_{I_j} \right) = \frac{\omega \left(n - M_C + A_{I-j} \right) - \left(\omega \left(nq - 1 \right) + 1 \right) a_{Ij}}{nq\omega + 1},$$

and the equilibrium total mitigation by individualistic countries is then

$$\hat{M}_I^{PL} \left(M_C, A_I \right) = \frac{n^2 q\omega - nq\omega M_C - A_I}{nq\omega + 1}.$$

A representative cooperating country, acting as a leader, anticipates the followers' reaction function and, in its second-stage mitigation game, solves

$$\begin{aligned} \min_{m_C} \quad & \left\{ c_{Cj} = \frac{\omega}{2} \left(n - npm_C - \hat{M}_I^{PL} \left(npm_C, A_I \right) \right)^2 \right. \\ & \left. - \left(n - npm_C - \hat{M}_I^{PL} \left(npm_C, A_I \right) \right) a_{Cj} + \frac{1}{2} m_C^2 + \frac{\theta}{2} a_{Cj}^2 \right\}. \end{aligned}$$

Its best response to the adaptation levels determined in the first stage is given by

$$\tilde{m}_C^{PL} \left(A_C, A_I \right) = \frac{n^2 p\omega - A_C \left(nq\omega + 1 \right) + np\omega A_I}{n^2 p^2 \omega + \left(nq\omega + 1 \right)^2},$$

and presents similar features as in the case without leadership.

The subgame-perfect Stackelberg equilibrium in mitigation is given by

$$\begin{aligned}
\bar{m}_C^{PL}\left(A_C, A_I\right) &= \frac{n^2 p\omega - \left(nq\omega + 1\right) A_C + np\omega A_I}{n^2 p^2 \omega + \left(nq\omega + 1\right)^2} \\
\bar{m}_{Ij}^{PL}\left(A_C, A_I, a_{Ij}\right) &= \frac{\left(nq\omega + 1\right) n\omega + np\omega A_C + \left(nq\omega + 1\right) \omega A_I}{n^2 p^2 \omega + \left(nq\omega + 1\right)^2} - a_{Ij} \qquad (18)
\end{aligned}$$

and the corresponding total emissions are given by

$$\bar{E}^{PL}\left(A_C, A_I\right) = \frac{n\left(nq\omega + 1\right) + npA_C + \left(nq\omega + 1\right) A_I}{n^2 p^2 \omega + \left(nq\omega + 1\right)^2}. \qquad (19)$$

We observe that, as in the case without leadership, adaptation as a prior investment can be used strategically to influence a country's mitigation policies. Again, the emissions of cooperating players are positively related to the adaptation levels of individualistic countries, and negatively related to their joint adaptation level, while the emissions of individualistic players are positively related to the adaptation levels of all other countries, but negatively related to their own adaptation level.

Moving to the first stage of the sequential game, the equilibrium mitigation levels (18) and (19) are taken into account by each individualistic country, which selects its investment in adaptive measures by solving

$$\min_{a_{Ij}} \left\{ c_{Ij} = \frac{\omega}{2}\left(\bar{E}^{PL}\left(A_C, A_I\right)\right)^2 - \left(\bar{E}^{PL}\left(A_C, A_I\right)\right) a_{Ij} + \frac{1}{2}\left(\bar{m}_{Ij}^{PL}\left(A_C, A_I, a_{Ij}\right)\right)^2 + \frac{\theta}{2} a_{Ij}^2 \right\},$$

which yields the equilibrium response function

$$\hat{a}_I^{PL}\left(A_C\right) = n \frac{\left(\omega + 1\right)\left(X + \left(Y + 1\right)^2 - \omega\left(Y + 1\right)\right)\left(Y + pA_C + 1\right)}{\left(X + \left(Y + 1\right)^2\right)\left(\theta\left(X + \left(Y + 1\right)^2\right) - nq\left(Y + 1\right)\right) + \left(X + \left(Y + 1\right)\left(Y - \omega\right)\right) W}$$

where constants X, Y and W are defined in (12)-(14). If cooperating countries increase their expenditures on adaptive measures, individualistic countries react by doing the same.

We then have

$$\begin{aligned}
\tilde{E}^{PL}(A_C) &= \frac{\left(n^2\omega(Y+1)+XA_C\right)(U+\theta G)}{Hn} \\
\tilde{m}_C^{PL}(A_C) &= p\frac{A_C\left(G\left(Y-\theta\omega(Y+1)\right)-\omega U\right)+n^2\omega^2(U+\theta G)}{H} \\
\tilde{m}_I^{PL}(A_C) &= \frac{\left(H+W(\omega+1)\left(\omega(Y+1)-G\right)\right)\left(XA_C+n^2\omega(Y+1)\right)}{GHn}
\end{aligned}$$

where

$$\begin{aligned}
H &= \theta\omega G^2+\omega WU-YG(Y+1) \\
U &= X+(Y+1)(Y-\omega) \\
G &= (Y+1)^2+X.
\end{aligned}$$

Finally, cooperating countries solve the optimization problem

$$\min_{a_C}\left\{c_{Cj}=\frac{\omega}{2}\left(\tilde{E}^{PL}(npa_C)\right)^2-\left(\tilde{E}^{PL}(npa_C)\right)a_C+\frac{1}{2}\left(\tilde{m}_C^{PL}(npa_C)\right)^2+\frac{\theta}{2}a_C^2\right\}$$

and the solution of the whole game is then

$$\begin{aligned}
a_C^{PL} &= \frac{n\omega^2(U+\theta G)\left((Y+1)H-XY(G+\omega U)\right)}{K_5} \\
a_I^{PL} &= \frac{n\omega(\omega+1)\left(XY(G+\omega U)-\theta\omega(Y+1)H\right)\left(\omega(Y+1)-G\right)}{K_5} \\
m_C^{PL} &= n^2p\omega^2(U+\theta G)\frac{-\omega UW+YG(Y+1)+\theta\omega\left(H-G^2\right)}{K_5} \\
m_I^{PL} &= n\omega\frac{\left(H+W(\omega+1)\left(\omega(Y+1)-G\right)\right)\left(\theta\omega H(Y+1)-XY(G+\omega U)\right)}{K_5G}
\end{aligned}$$

where

$$K_5=\left(\theta\omega\left(H^2-\theta\omega XG^3\right)+X\left(\omega^2U^2(X+1)+Y^2G^2-2\omega U(H+YG)\right)\right).$$

Claim 3 *When cooperating countries act as leaders and adaptation is a prior investment, a cooperating country adapts always less than an individualistic country. When their number is small enough, cooperators mitigate less than individualists, and therefore their total cost is lower than that of the individualistic countries.*

Notice that when cooperating countries are leaders, the relationship holding between the adaptive investments of cooperators and individualists is opposite to what is found with prior adaptive investments without leadership.

4.2 Adaptation as a concurrent investment

In this section adaptation and mitigation are decided on at the same time; however, individualistic countries' choices for both policies are anticipated by cooperating players. The reaction of an individualistic country to a joint announcement by the leaders is obtained by solving (17), which yields

$$\begin{aligned} \tilde{m}_I^{SL}(M_C) &= \frac{(\theta\omega - 1)(n - M_C)}{\theta + nq(\theta\omega - 1)} \\ \tilde{a}_I^{SL}(M_C) &= \frac{n - M_C}{\theta + nq(\theta\omega - 1)}. \end{aligned}$$

It is important to highlight that, as in the game without leadership, individualists' mitigation choices are not affected by what is announced by the leaders in terms of their adaptation policy. Even when cooperating countries are leaders, adaptation has no strategic effect on individualists' decisions. Individualistic countries optimal adaptation expenditures are still a proportion of total emissions. However, if leaders declare that they will increase their mitigation levels, followers will respond by reducing their effort in both environmental policies.

These reactions are anticipated by the cooperating countries, whose optimization problem

is given by

$$\min_{m_C,a_C}\left\{c_{Cj}=\frac{\omega}{2}\left(n-npm_C-nq\tilde{m}_I^{SL}\left(npm_C\right)\right)^2-\left(n-npm_C-nq\tilde{m}_I^{SL}\left(npm_C\right)\right)a_C+\frac{1}{2}m_C^2+\frac{\theta}{2}a_C^2\right\}$$

yielding

$$\begin{aligned}
a_C^{SL} &= n\frac{\theta+nq\left(\theta\omega-1\right)}{\theta\left(\left(nq\omega+1\right)\left(\theta\left(nq\omega+1\right)-2nq\right)+n^2p^2\left(\theta\omega-1\right)\right)+n^2q^2}\\
m_C^{SL} &= \frac{\theta n^2p\left(\theta\omega-1\right)}{\theta^2\left(n^2p^2\omega+\left(nq\omega+1\right)^2\right)-\theta n\left(2q\left(nq\omega+1\right)+np^2\right)+n^2q^2}.
\end{aligned}$$

The solution of the whole game is:

$$\begin{aligned}
a_C^{SL} &= a_I^{SL}=n\frac{\theta+nq\left(\theta\omega-1\right)}{K_6}\\
m_C^{SL} &= \frac{\theta n^2p\left(\theta\omega-1\right)}{K_6}\\
m_I^{SL} &= \frac{n\left(\theta-nq+\theta nq\omega\right)\left(\theta\omega-1\right)}{K_6}\\
\text{where } K_6 &= \theta\left(\left(nq\omega+1\right)\left(\theta\left(nq\omega+1\right)-2nq\right)+n^2p^2\left(\theta\omega-1\right)\right)+n^2q^2.
\end{aligned}$$

Claim 4 *When cooperating countries act as leaders and adaptation and mitigation are simultaneous decisions, both types of countries behave in the same way in terms of adaptation. When the number of cooperating countries is small enough, both their mitigation levels and their total cost are lower than that of individualistic countries.*

For concurrent investments under leadership, adaptation levels of both types of players are equal, as in the no-leadership case. However, when the number of cooperating leaders is small, individualists are no longer able to free ride and to mitigate less than the others.

5 Results

In this section we assess the impact of commitment and timing of adaptive investments. We focus, in particular, on three different variables, namely, the performances of countries in terms of environmental cost and their level of adaptation and mitigation.

The first set of results provides an evaluation of the two types of adaptive investments for the singular-type cases; this completes and extends Zehaie (2009)'s result about the ranking of adaptation levels in these cases.

Claim 5 *When all players are individualists and adaptive measures are a prior investment, then countries:*

(a) suffer a greater environmental cost;

(b) achieve a greater level of adaptation;

(c) mitigate less

than when adaptation and mitigation are decided simultaneously. Moreover, for both types of adaptive investments, the environmental costs and the adaptation levels are higher, whereas the mitigation levels are lower than in the first best solution.

When all countries act individualistically and investments in adaptation are decided on before mitigation levels, countries suffer the highest environmental cost. This is due to the fact that countries use their investments in self-protective measures strategically, so that, by reducing their vulnerability to climate change effects, they can mitigate less. A better option in terms of environmental cost is to carry out adaptation and mitigation efforts simultaneously, which implies smaller adaptive expenditures and a greater mitigation effort.

We now turn to the mixed cases involving both cooperators and individualists. Thanks to the presence of coexisting behaviors, we can confront the results between the two types of countries and highlight new insights against the singular type cases.

The second set of findings compares the equilibrium solutions found in Section 3 (no leadership) with the first best solution.

Claim 6 *Regardless of the type of adaptive investment:*

(a) in terms of costs, cooperating countries are never able to outperform the first best solution, but individualistic countries can outperform the first best solution when there is a relatively large number of cooperating countries;

(b) both individualistic and cooperating countries' adaptive levels are higher than in the first best solution;

(c) individualistic countries always mitigate less than in the first best solution, but cooperating countries may curtail their emissions more when mitigation is relatively expensive.

The first observation (a) is due to the presence of coexisting behaviors. Cooperators choose aggressive environmental policies that allow individualistic countries to free ride, so that they can be in a better position than in the first best solution when the number of cooperating countries is high enough. It is worthy of note that this free-riding advantage exists for both types of adaptive investment. The third observation (c) about the mitigation levels is an interesting result since cooperators always adapt more than in the first best solution; however, due to the coexistence with individualistic countries, cooperators are led to inefficiently high levels of emission reduction, even though their adaptation investment is high.

The third set of results compares the individual solutions of cooperators versus individualists found in Section 3 (no leadership) under the two different timing scenarios.

Claim 7 *When adaptive measures are a prior investment:*

(a) both types of countries suffer a greater environmental cost;

(b) both types of countries achieve a greater level of adaptation;

(c) cooperating countries always mitigate less, but it can happen that individualistic countries mitigate more

than when adaptation and mitigation decisions are taken simultaneously.

The first observation (a) is interesting, as it confirms Claim 5 for the partial cooperation case: prior commitment to adaptive measures is not welfare enhancing. This inefficiency is again due to the strategic effect of adaptive measures: players choose adaptive levels that are too high in order to influence the equilibrium mitigation levels in the second stage. For cooperating countries, this translates in lower mitigation levels, an expected result because of the substitution effect between mitigation and adaptation. However, for individualistic countries, we can show that they do not take advantage of this substitution effect when the environmental sensitivity is relatively high.

When we repeat the same types of analysis under the assumption that cooperating countries become leaders in responding to climate change while individualistic countries act as followers, most of the previously reported comparisons become ambiguous. Clear conclusions can only be drawn when comparing the equilibrium solutions with and without leadership under the assumption that adaptation and mitigation decisions are taken simultaneously.

Claim 8 *When adaptation and mitigation decisions are taken simultaneously and cooperating countries act as leaders:*

(a) the environmental cost is lower for cooperating countries, higher for individualistic countries, but the overall aggregate cost is greater;

(b) both types of countries adapt more;

(c) cooperating countries mitigate less, individualistic countries mitigate more, but total pollution level is higher

than in a game without leadership.

Cooperating countries, by becoming first movers and anticipating the followers' reaction, mitigate less and push the followers to mitigate more than in a game without leadership. This yields a higher total pollution, and greater expenditures in adaptation for both types of countries, since adaptation is proportional to the total pollution level. In terms of individual performance, leaders are better off, and followers are worse off, but at the aggregate level, the overall environmental cost is greater with leadership than without leadership, implying that leadership is not globally efficient.[6] This observation is in line with the outcome of the Paris climate change agreement adopted in December 2015 by more than 190 countries. In the Paris agreement, there are no references to any "historical responsibilities" or to "Annex" and "non-Annex" countries, even if the concept of differentiation is still present across all the elements of the agreement (e.g. mitigation, adaptation, finance, technology, capacity building and transparency).

To conclude this section, it is worth mentioning that adaptation as a prior investment yields the worst aggregate outcome in all the scenarios analyzed here (non-cooperation, partial cooperation, and leadership)[7]. This is an important result, as it qualifies the statement, in the IPCC (2014), that adaptation and mitigation are complementary strategies for reducing the risks of climate change; according to our model, to achieve more efficient results, these strategies should be decided on simultaneously.

6 Conclusions

In this paper we developed a model where countries minimize their environmental cost by adopting two environmental policies, namely, mitigation and adaptation, with the objective

[6] However, it would be convenient for a group of collaborating countries to make the first move and become leaders.

[7] Numerical investigations show that, under leadership, prior investment is inefficient at the aggregate level, even if it may happen that leaders suffer a lower cost than in the concurrent investment case.

of understanding the implications of different decision sequences for these policies, when players differ in their cooperative behavior.

We found that adaptation can be used strategically, that is, by committing to adaptive measures before deciding on mitigation levels, countries can allocate greater resources to adaptation and self-protection (a private good) in order to reduce their contribution to public mitigation efforts.

One of the main results of our analysis is that the highest environmental cost suffered by countries always occurs when investments in adaptation are committed to before any decisions about mitigation levels are made (this is true both in the fully non-cooperative case and in the partial cooperation case, with and without leadership). As a consequence, simultaneous investments in adaptive and mitigating measures seem to be the best way to answer the problem of the effects of climate change. This is an important result because it reinforces the message stated in the IPCC (2014), while adding that the complementary environmental policies should be carried out at the same time, with a unified approach.

Finally, we showed that with simultaneous investments in adaptive and mitigating measures, having some countries taking leadership in responding to the effects of climate change is not beneficial at an aggregate level. This contrasts with what has been done for the promotion of international environmental agreements in the Kyoto Protocol, that is the distinction between "Annex" and "No-Annex" countries. Our result is more in line with the approach adopted in the new climate change agreement signed in Paris in December 2015 by over 190 countries and meant to replace the Kyoto Protocol in 2020. In the new agreement, there is no mention to any "historical responsibilities" even if the idea of differentiated countries is mentioned across all the elements of the agreement. However, from an individual point of view, countries that become leaders are able to lower their overall cost, so that it is in the interest of cooperating countries to take a first step in countering the effects of climate change.

As a final remark, notice that in this paper the number of countries having a coopera-

tive behaviour is an exogenous parameter, and, as a consequence, our results apply to any number of cooperators. The question of stability of an eventual agreement between these cooperating countries is not addressed and this is one limitation of the paper, as all the possible configurations we consider would not necessarily correspond to a stable coalition. An interesting avenue for future research would be to determine to what extent the timing of adaptation activities could impact the incentives for countries to participate in self-enforcing or in cooperative agreements.

7 Appendix

In the following proofs, we use the auxiliary variables $k \equiv \theta\omega - 1 > 0$ and X, Y and W as defined in (12)-(14) to simplify the notation.

Claim 1. $a_C^{PN} > a_I^{PN}$:

$$K_1 \frac{a_C^{PN} - a_I^{PN}}{n\omega} = kW\left(Y - \omega\right)\left(X - \omega\right) > 0.$$

$m_C^{PN} \gtrless m_I^{PN}$:

$$K_1 \frac{m_C^{PN} - m_I^{PN}}{kn\omega W} = \theta\omega W\left(np - 1\right) - XY + np\omega\left(X + Y - \omega\right).$$

This difference is negative if

$$0 < \theta < \frac{XY - np\omega\left(X + Y - \omega\right)}{\omega W\left(np - 1\right)} = np\omega \frac{nq - 1 - np}{W},$$

which requires that $nq - 1 > np$ (more defectors than cooperators).

$c_C^{PN} > c_I^{PN}$:

$$
\begin{aligned}
2K_1^2 \frac{c_C^{PN} - c_I^{PN}}{n^2 k^2 W \omega (X - \omega)} &= kW \left(kW^2 + \omega \left(2X + \omega^2 + Y^2 + X(2X - \omega) + 2Y(X - \omega)\right)\right) \\
&\quad + (\omega + 1)(X + 1)\left((Y - \omega)(3Y + X\omega + 1) + Y^2 (X - 2\omega)\right) \\
&\quad + kW \left(4(X + Y + XY) + X\left(2X + Y^2\right) + 2\left(Y^2 + 1\right)\right) \\
&\quad + \omega^2 (X + 1)\left((\omega + 1)(Y + 1) + X^2\right) \\
&\quad + (X + 1)\left(2(X + Y) + Y\left(3X + Y^2\right) + X^2 + 1\right) \\
&\quad + (X + 1)\left(\omega\left(2(X + Y) + Y\left(6X + Y^2\right) + 2X^2 + 1\right)\right) \\
&> 0.
\end{aligned}
$$

■

Claim 2. $m_C^{SN} > m_I^{SN}$:

$$K_4 \left(m_C^{SN} - m_I^{SN}\right) = nk(np - 1) > 0.$$

Total cost is higher for cooperating countries since the abatement and environmental costs are equal for both types of countries. ■

Claim 3. $a_C^{PL} < a_I^{PL}$

$$K_5 \frac{a_C^{PL} - a_I^{PL}}{kn\omega} = -G^2 U\omega (Y + 1) k - U\omega W (G + U\omega)(Y + 1) - GXY (G + U\omega) < 0.$$

Numerical investigations show that mitigation levels and total costs differences can be positive or negative. For mitigation levels, $m_C^{PL} \leq m_I^{PL}$ when

$$np \leq \frac{(H + W(\omega + 1)(\omega(Y + 1) - G))(\theta\omega H(Y + 1) - XY(G + \omega U))}{(U + \theta G)(-\omega UW + YG(Y + 1) + \theta\omega(H - G^2))G\omega}.$$

■

Claim 4. $m_C^{SL} \gtrless m_I^{SL}$:

$$\omega K_6 \frac{m_C^{SL} - m_I^{SL}}{kn} = k\left(np - nq\omega - 1\right) + np - 1$$

Since adaptation levels are the same for the two types of countries, both $m_C^{SL} < m_I^{SL}$ and $c_C^{SL} < c_I^{SL}$ hold when

$$np < 1 + \frac{k}{k+1} nq\omega.$$

■

Claim 5.

(a) $c^{PI} > c^{SI} > c^{FB}$:

$$\begin{aligned} 2K_3^2 K_5^2 \frac{c^{PI} - c^{SI}}{k^2 n^2 (n-1)^2} &= k(\omega+2)(n\omega+1)^2 + (\omega+1)(\omega(2n-1)+2) > 0 \\ 2\omega K_2 K_5^2 \frac{c^{SI} - c^{BF}}{kn^2} &= k(n-1)^2(k+1) > 0. \end{aligned}$$

(b) $a^{PI} > a^{SI} > a^{FB}$:

$$\begin{aligned} K_3 K_5 \left(a^{PI} - a^{SI}\right) &= nk\omega(n-1)(n\omega+1) > 0 \\ K_2 K_5 \frac{a^{SI} - a^{BF}}{n} &= kn(n-1). \end{aligned}$$

(c) $m^{PI} < m^{SI} < m^{FB}$:

$$\begin{aligned} K_3 K_5 \frac{m^{PI} - m^{SI}}{kn} &= -\omega(n-1) < 0 \\ K_2 K_5 \frac{m^{SI} - m^{BF}}{kn} &= -(n-1)\frac{k+1}{\omega} < 0. \end{aligned}$$

■

Claim 6.

(a) $c_C^{SN} > c^{FB}$:

$$2\omega K_2 K_4^2 \frac{c_C^{SN} - c^{FB}}{k^2 n^3} = knq\omega\left(np-1\right)\left(q+np\left(p+1\right)\right)+q\left(n+np-2\right)\left(k+1\right)>0.$$

$c^{FB} > c_C^{PN}$, $c^{FB} \gtrless c_I^{SN}$ and $c^{FB} \gtrless c_I^{PN}$ were checked numerically. For instance, for $n = 100$, $np = 60$, $\omega = 0.4$ and $\theta = 4$, the cost of the individualist countries is smaller than in the first best solution for both types of adaptation.

(b) $a^{FB} < a_C^{SN} = a_I^{SN}$ is immediate since $K_4 = \theta + n\left(\left(1-p\right)+np^2\right)k < \theta + kn^2 = K_2$. We already showed that $a_I^{PN} < a_C^{PN}$. $a^{FB} < a_I^{PN}$ was checked numerically.

(c) $m^{FB} > m_I^{SN}$: this is immediate from $K_4 < K_2$.

$m^{FB} > m_I^{PN}$ was checked numerically.

$m^{FB} \gtrless m_C^{PN}$: for different set of parameters, we obtained both signs for the difference $m^{FB} - m_C^{PN}$ and $m^{FB} - m_C^{SN}$. The mitigation level of cooperating countries is higher than in the first best solution when the mitigation cost coefficient γ_M is large compared to the environmental sensitivity γ_D.

■

Claim 7.

(a) $c_C^{PN} > c_C^{SN}$ and $c_I^{PN} > c_I^{SN}$ were checked numerically.

(b) $a_C^{PN} > a_I^{PN} > a_I^{SN} = a_C^{SN}$: we already proved that $a_C^{PN} > a_I^{PN}$.

$$K_1 K_4 \frac{a_I^{PN} - a_I^{SN}}{n} = k\omega W\left(X+Y-\omega\right)\left(Y+kW+XY+1\right)+X^2YkW>0.$$

(c) $m_C^{PN} < m_C^{SN}$:

$$K_1 K_4 \frac{m_C^{PN} - m_C^{SN}}{kn^2 p} = -YkW\omega\left(\omega\left(nq-1\right)\left(n^2p^2-1\right)+n^2p^2\right)-XY\left(\omega+1\right)\left(W-\omega\right)<0$$

$m_I^{PN} \gtrless m_I^{SN}$:

$$\begin{aligned} K_1 K_4 \frac{m_I^{PN} - m_I^{SN}}{kn\omega^2} &= kW\left(n^2p^2\omega\left(np-1\right)\left(np+1\right)\left(nq-1\right)\right) \\ &\quad - \left(n^2p^2\omega+1\right)\left(nq\omega+1\right)\left(n^2p^2+nq-1\right) - kW\left(n^2p^2+nq-1\right). \end{aligned}$$

$m_I^{PN} > m_I^{SN}$ if both these conditions are satisfied:

$$\begin{aligned} \omega &> \frac{n^2p^2+nq-1}{n^2p^2\left(np-1\right)\left(np+1\right)\left(nq-1\right)} > 0 \\ \left(\theta\omega-1\right) &> \frac{\left(n^2p^2\omega+1\right)\left(nq\omega+1\right)\left(n^2p^2+nq-1\right)}{W\left(n^2p^2\omega\left(np-1\right)\left(np+1\right)\left(nq-1\right)-\left(n^2p^2+nq-1\right)\right)} > 0. \end{aligned}$$

■

References

[1] Agrawala, S., Bosello, F., Carraro, C., De Cian, E. & Lanzi, E. (2011). "Adapting to climate change: Costs, benefits, and modelling approaches." *International Review of Environmental and Resource Economics*, 5(3), 245-284.

[2] Barrett, S. (2008). *Dikes Vs. Windmills: Climate Treatise and Adaptation.* Johns Hopkins University, School of Advanced International Studies.

[3] Bréchet, T., Hritonenko, N. & Yatsenko, Y. (2013). "Adaptation and mitigation in long-term climate policy." *Environmental and Resource Economics*, 55(2), 217-243.

[4] De Bruin, K. C., Weikard, H. P. & Dellink, R. (2011). *The Role of Proactive Adaptation in International Climate Change Mitigation Agreements.* CERE Working Paper 2011:9.

[5] Buob, S. & Siegenthaler, S. (2011). *Does Adaptation Hinder Self-enforcing International Environmental Agreements?* Department of Economics and Oeschger Centre for Climate Change Research, University of Bern.

[6] Buob, S. & Stephan, G. (2011). "To mitigate or to adapt: How to confront global climate change." *European Journal of Political Economy*, 27(1), 1-16.

[7] Ebert, U. & Welsch, H. (2012). "Adaptation and mitigation in global pollution problems: Economic impacts of productivity, sensitivity, and adaptive capacity." *Environmental and Resource Economics*, 52(1), 49-64.

[8] Eisenack, K. & Kähler, L. (2012) "Unilateral emission reductions can lead to Pareto improvements when adaptation to damages is possible." Tech. Rep.Wirtschaftswissenschaftliche Diskussionpapiere V - 344–12, University Oldenburg.

[9] European Commission Climate Action (2015) "Adaptation to climate change." Available at http://ec.europa.eu/clima/policies/adaptation/index_en.htm, last update on 10/09/2015.

[10] Farnham, M. & Kennedy, P. (2014). "Adapting to Climate Change: Equilibrium Welfare Implications for Large and Small Economies." *Environmental and Resource Economics*, 1-19.

[11] Ingham, A., Ma, J. & Ulph, A. M. (2013). "Can Adaptation and Mitigation Be Complements." *Climatic Change* 120, 39-53.

[12] IPCC (2001). *Climate Change 2001: Synthesis Report*. A Contribution of Working Groups I, II, and III to the Third Assessment Report of the Integovernmental Panel on Climate Change, Watson, R.T. and the Core Writing Team (eds.), Cambridge University Press.

[13] IPCC (2007). *Climate Change 2007: Synthesis Report*. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Core Writing Team, Pachauri, R.K. and Reisinger, A. (eds.), IPCC, Geneva, Switzerland.

[14] IPCC (2014). *Climate Change 2014: Synthesis Report*. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Core Writing Team, Pachauri, R.K. and Meyer, L.A. (eds.), IPCC, Geneva, Switzerland.

[15] Kane, S. & Shogren, J. F. (2000). "Linking adaptation and mitigation in climate change policy." *Climatic Change*, 45(1), 75-102.

[16] Lecocq, F. & Shalizi, Z. (2007). *Balancing Expenditures on Mitigation of and Adaptation to Climate Change: An Exploration of Issues Relevant to Developing Countries*. World Bank Policy Research Working Paper (4299).

[17] Marrouch, W. & Ray Chaudhuri, A. (2011). *International Environmental Agreements in the Presence of Adaptation*. FEEM Working Paper (35.2011).

[18] President Barack Obama (2013) Climate Action Plan, available at https://www.whitehouse.gov/sites/default/files/image/president27sclimateactionplan.pdf

[19] Tulkens, H. & Van Steenberghe, V. (2009). *'Mitigation, Adaptation, Suffering': In Search of the Right Mix in the Face of Climate Change*. FEEM Working Paper (79.2009).

[20] Yohe, G. & Strzepek, K. (2007). "Adaptation and mitigation as complementary tools for reducing the risk of climate impacts." *Mitigation and Adaptation Strategies for Global Change*, 12(5), 727-739.

[21] Zehaie, F. (2009). "The timing and strategic role of self-protection." *Environmental and Resource Economics*, 44(3), 337-350.