Les Cahiers du GERAD ISSN: 0711–2440

Adaptation and mitigation strategies against climate change: A survey of game theoretic models

M. Breton, L. Sbragia

G–2025–51

July 2025

La publication de ces rapports de recherche est rendue possible grâce au soutien de HEC Montréal, Polytechnique Montréal, Université McGill, Université du Québec à Montréal, ainsi que du Fonds de recherche du Québec – Nature et technologies.

Dépôt légal – Bibliothèque et Archives nationales du Québec, 2025
– Bibliothèque et Archives Canada, 2025

The publication of these research reports is made possible thanks to the support of HEC Montréal, Polytechnique Montréal, McGill University, Université du Québec à Montréal, as well as the Fonds de recherche du Québec – Nature et technologies.

Legal deposit – Bibliothèque et Archives nationales du Québec, 2025
– Library and Archives Canada, 2025

GERAD HEC Montréal
3000, chemin de la Côte-Sainte-Catherine
Montréal (Québec) Canada H3T 2A7

Tél. : 514 340-6053
Téléc. : 514 340-5665
info@gerad.ca
www.gerad.ca

Adaptation and mitigation strategies against climate change: A survey of game theoretic models

Michele Breton [a]

Lucia Sbragia [b]

[a] *Department of Decision Sciences, HEC Montréal & GERAD, Montréal (Qc), Canada, H3T 2A7*

[b] *Department of Economics, Durham University Business School, Durham, England, D1H 3LB*

michele.breton@hec.ca

lucia.sbragia@durham.ac.uk

July 2025
Les Cahiers du GERAD
G–2025–51

Abstract : In addressing climate change, countries rely on two primary strategies: mitigation, which aims to reduce greenhouse gas emissions, and adaptation, which seeks to minimize the adverse effects of climate-related impacts. It is widely recognized that these two strategies should be implemented in tandem to effectively combat global warming. This paper reviews the existing literature on the strategic interplay between mitigation and adaptation, with a particular focus on how adaptation—when treated as a private good—affects the strategic behavior of countries confronting climate change as a global public bad.

Keywords : Climate change, adaptation, mitigation, environmental agreements

Résumé : Dans le cadre de la lutte contre le changement climatique, deux stratégies principales sont disponibles : l'atténuation, qui vise à réduire les émissions de gaz à effet de serre, et l'adaptation, qui cherche à minimiser les effets négatifs des impacts climatiques. Il est largement reconnu que ces deux stratégies doivent être mises en oeuvre conjointement pour lutter efficacement contre le réchauffement climatique. Cet article propose une revue la littérature existante sur l'interaction stratégique entre atténuation et adaptation, en mettant particulièrement l'accent sur la manière dont l'adaptation — lorsqu'elle est considérée comme un bien privé — influence le comportement stratégique des agents face au changement climatique, considéré comme un mal public mondial.

Mots clés : Changement climatique, adaptation, atténuation, accords environnementaux

1 Introduction

In the global fight against climate change, two principal strategies have emerged: *mitigation* and *adaptation*. Mitigation encompasses actions aimed at reducing the emission of greenhouse gases (GHGs) into the atmosphere, thereby targeting the root cause of climate change. Adaptation, by contrast, refers to adjustments in ecological, social, or economic systems in order to cope with the impacts of climate change, thus reducing its negative consequences.

These two strategies are widely regarded as complementary, in the sense that they should be implemented concurrently. Indeed, even if global GHG emissions were to cease immediately, it would take thousands of years for atmospheric carbon dioxide (CO_2) concentration to return to "acceptable" (for instance, pre-industrial) levels due to the slow pace of Earth's natural elimination and cooling processes. Consequently, adaptation is indispensable for managing the residual impacts of climate change.

In recent years, adaptation has gained increasing prominence, particularly in light of the insufficient progress towards the mitigation targets set by the Paris Agreement (2016), the most recent international treaty addressing climate change. Evidence of this paradigm shift is reflected in the growing emphasis on adaptation-related terminology introduced in successive reports of the Intergovernmental Panel on Climate Change (IPCC), starting from the IPCC Second Assessment report (1995) where adaptation becomes a clear item in the agenda of Working Group II.

The IPCC currently defines adaptation as follows:

"*In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate and its effects.*" (IPCC AR6, 2023).

Illustrative examples of adaptation measures (extracted from the IPCC's Third Assessment report (AR3, 2011) include investments in water storage or diversion infrastructure to increase water supply reliability; the construction of flood protection systems such as dams and levees; research and development of crop varieties with greater tolerance to heat, drought, and pests; coastal protection through both engineered ("hard") structures like seawalls and nature-based ("soft") solutions such as ecosystem restoration and afforestation; and the strengthening of public health systems.

The integration of adaptation decisions into economic models of climate policy raises several new research questions. The first concerns the nature of the relationship between mitigation and adaptation—are they strategic complements or substitutes in economic terms? The second question examines how the inclusion of adaptation influences the strategic interactions among agents with respect to mitigation. A third issue relates to the optimal sequencing of mitigation and adaptation decisions—should they be made simultaneously or sequentially? The timing of these decisions gives rise to various multi-stage game-theoretic frameworks. Finally, in the context of international environmental agreements (IEAs), a relevant question is to examine whether the availability of adaptation affects the size and stability of cooperating coalitions.

This paper focuses on *private adaptation,* defined as adaptation measures that reduce an individual agent's damages from climate change without altering the aggregate level of emissions. It reviews a selection of theoretical models that incorporate both mitigation and adaptation and proposes a unified analytical framework to explore their interdependencies. The objective is to shed light on the implication of adaptation relationships in the context of the key issues raised by the integration of adaptation as a damage-attenuation mechanism within stylized representations of climate policy interactions.[1]

[1] This review is selective and focuses on peer-reviewed journal articles that share a common modeling framework, thereby allowing comparisons. It does not aim to provide an exhaustive survey of the adaptation literature.

The remainder of the paper is structured as follows. Section 2 presents the basic model of strategic interactions in the context of climate change. Section 3 examines the complementarity issue between mitigation and adaptation strategies and explores how adaptation influences the mitigation game. Section 4 reviews the literature on the timing of mitigation and adaptation strategies. Section 5 discusses recent findings on the impact of adaptation on the stability of IEAs. Section 6 concludes.

2 A stylized model of strategic interactions in the context of climate change

In the simplest standard framework modeling interactions between countries (or regions) in the context of climate change, a country's welfare typically involves two components: a production benefit that depends solely on own production, and a climate-related damage cost that is a function of aggregate global pollution. In stylized representations, both components can be expressed as function of countries' emission levels. The production benefit is assumed to increase with a country's own emissions, while the damage cost is assumed to increase with total global emissions. These stylized models assume a direct functional relationship between individual production and emissions, as well as between global warming and global pollution levels.

2.1 The emission mitigation model

Define:

N : total number of countries

e_i : emission level of country i (decision variable)

E : global pollution level

$B_i(e_i)$: benefit of country i from own emissions

$D_i(E)$: damage of country i from global pollution.

The benefit function is assumed to be increasing and concave in emissions

$$B_i' > 0; B_i'' \leq 0, \ i = 1, ..., N, \tag{1}$$

while the damage function is assumed to be increasing and convex in global pollution

$$D_i' > 0; D_i'' \geq 0, \ i = 1, ..., N.$$

Most contributions in the literature adopt a static framework, in which global pollution is defined as the aggregate flow of emissions across all countries:

$$\begin{aligned} E &= \sum_{j=1}^{N} e_j \\ &= e_i + E_{-i} \end{aligned}$$

where $E_{-i} = E - e_i$ represents the total emissions from all countries except country i. Studies employing a dynamic formulation define global pollution as the cumulated stock of emissions over time.

The individual welfare function of a given country is then given by

$$W_i(e_i, E) = B_i(e_i) - D_i(E).$$

This stylized model, which we will call the *M-model*, is the foundation of a large literature on the interaction between countries in the context of climate change, including a substantial number of papers discussing the stability of IEAs.

It is worth noting that many contributions in this literature adopt an equivalent formulation in which the countries decide on their abatement level, rather than their emission level. Using a reference emission level $\overline{e}$—such as the business-as-usual scenario or any other upper bound on the emissions—and the corresponding total pollution $\overline{E} = N\overline{e}$, an equivalent formulation is obtained by defining the abatement level

$$q_i = \overline{e} - e_i.$$

Substituting e_i by $\overline{e} - q_i$ in the welfare function yields

$$\begin{aligned} W_i(e_i, E) &= B_i(e_i) - D_i(E) \\ \widetilde{W}_i(q_i, Q) &= B_i(\overline{e} - q_i) - D_i(\overline{E} - Q) \end{aligned}$$

where $Q \equiv \sum_i^N q_i = \overline{E} - E$.

By setting the *abatement cost* to the difference $G_i(q_i) \equiv B_i(\overline{e}) - B_i(\overline{e} - q_i)$ and the *benefits from abatement* to the difference $F_i(Q) \equiv D_i(\overline{E}) - D_i(\overline{E} - Q)$, the abatement mitigation model consists in minimizing the individual cost function

$$\begin{aligned} V_i(q_i, Q) &\equiv G(q_i) - F_i(Q) \\ &= B_i(\overline{e}) - B_i(\overline{e} - q_i) - D_i(\overline{E}) + D_i(\overline{E} - Q) \\ &= -\widetilde{W}_i(q_i, Q) + B_i(\overline{e}) - D_i(\overline{E}), \end{aligned}$$

yielding an equivalent minimization model since $B_i(\overline{e}) - D_i(\overline{E})$ is an exogenous constant.[2] Either abatement or emission level decision variables can be used to characterize mitigation strategies, which result in a reduction of the global pollution level.

Within this general framework, the literature distinguishes between two behavioral assumptions regarding countries' strategic interactions. In the noncooperative (individualistic) scenario, each country maximizes its own welfare independently, treating the emission levels of other countries as given, leading to a Nash equilibrium. In contrast, under a cooperative scenario, countries coordinate their decisions, jointly selecting an emission vector maximizing aggregate total welfare.[3] Assuming an interior solution, from the first-order conditions of these respective maximization problems in the static case, the equilibrium emission levels satisfy

$$\begin{aligned} B_i'(e_i) &= D_i'(E) \text{ in the individualistic case} \\ B_i'(e_i) &= ND_i'(E) \text{ in the cooperative case.} \end{aligned}$$

It is easy to show (see, for instance, Ebert & Welsch 2011) that, in both cooperative and individualistic settings, countries' optimal emission response functions are downward-sloping with respect to the emission levels of other countries, with a slope greater than -1, implying that emissions are strategic substitutes: a reduction in emissions by other countries induces a given country to increase its own emissions. This phenomenon is commonly referred to as *carbon leakage*.

The M-model does not consider the possibility of adaptation—an additional policy instrument that countries can employ to attenuate the negative impacts of climate change. This instrument is presented in the next section.

[2] In this paper, we use the emission decision variable. Models from the literature using the abatement decision variable are converted accordingly.

[3] In some papers, an additional information structure is superimposed on the behavior of cooperating or individualistic countries, where countries or groups of countries may act as leaders by committing to their emission decisions before the others, giving rise to a Stackelberg equilibrium.

2.2 Introducing adaptation

The concept of adaptation was first formally introduced in the IPCC Second Assessment report (1995). Since then, its definition has evolved, precising its scope and means, as well as acknowledging the role of human intervention in natural systems (see Appendix A.1).

We now extend the M-model to incorporate adaptation as a strategic variable. In accordance with the IPCC's definition, adaptation is modeled as a private good: unlike mitigation, which reduces the global amount of pollution E, adaptation reduces a country's own exposure to climate-related damages change, without altering the global emission level.

Define:

a_i : adaptation level of country i (decision variable)

$D_i(E, a_i)$: damage of country i from global pollution, which now also depends on own adaptation

$C_i(a_i)$: cost of adaptation.

The cost of adaptation is assumed to be increasing and convex in the adaptation level:

$$C_i' > 0; C_i'' > 0, \ i = 1, ..., N. \tag{2}$$

The damage function is assumed to be increasing and convex in total pollution and decreasing and convex in adaptation:

$$D_{iE} > 0; D_{iEE} \geq 0, \ i = 1, ..., N \tag{3}$$

$$D_{ia} < 0; D_{iaa} \geq 0, \ i = 1, ..., N. \tag{4}$$

Moreover, in most models of the literature, the marginal impact of adaptation is assumed to be decreasing with the pollution level

$$D_{iEa} = D_{iaE} < 0, \ i = 1, ..., N, \tag{5}$$

which is a reasonable assumption in the context of climate change (an increase in the pollution level reduces the marginal impact of adaptation on environmental damages).

The individual welfare function of a given country in the static case then becomes

$$W_i\left(e_i, E, a_i\right) = B_i(e_i) - D_i(E, a_i) - C_i(a_i) \tag{6}$$

and is assumed to be strictly concave, satisfying

$$D_{iEE} - B_i'' > 0, \quad D_{iaa} + C_i'' > 0, \quad \left(D_{iEE} - B_i''\right)\left(D_{iaa} + C_i''\right) > \left(D_{iEa}\right)^2. \tag{7}$$

This stipulation will be called the *MA-model.*[4]

Assuming an interior solution, the optimal level of adaptation at a given E is characterized, in both the individualistic and the cooperative scenarios, by the following first order condition (FOC):

$$D_{ia}(E, a_i) + C_i'(a_i) = 0.$$

This condition implies that the optimal adaptation level is independent of the emission decision of an individual country, but depends on the global pollution level E.

Regarding emission decisions, the FOCs at a given (E, a_i) yield

$$B_i'(e_i) = D_{iE}(E, a_i) \text{ in the individualistic case}$$

$$B_i'(e) = ND_{iE}(E, a_i) \text{ in the cooperative case.}$$

As in the M-model, the cooperative solution internalizes the full social cost of emissions, while the individualistic solution reflects only the private marginal damage.

[4]Note that the adaptation level can be expressed in monetary units, using adaptation expenditures as the decision variable. In such case, the adaptation cost $C(a_i) \equiv a_i$ can be directly included in the damage cost function, and the last term of Equation (6) disappears. In this paper, we use the adaptation level decision variable.

2.3 Quadratic specification

Many results in the literature concerning the interplay between mitigation and adaptation in the context of climate change are analytical, applying to the general MA-model under conditions (1)-(5) and (7). In some cases, numerical results and illustrations are provided for specific forms of the MA-model. One of the most common specification assumes that the benefit and adaptation cost functions are quadratic. Under this quadratic specification, the general form of the welfare function (6) is

$$W_i\left(e_i, E, a_i\right) = e_i\left(2 - e_i\right) - D_i(E, a_i) - \delta a_i^2 \tag{8}$$

for $0 \leq e_i \leq 1$ and $a_i \geq 0$. This specification, called the *MAQ-model*, is obtained by normalizing the emission level variables and the numeraire (see Appendix A.2). When $D_E = D_a$, the parameter δ measures the ratio of the unit cost of mitigation with respect to adaptation.

The following sections employ the unified framework of the MA- and MAQ-models to review the literature on the optimal mix of adaptation and mitigation measures, on the role of timing of these measures in the equilibrium solution, as well as the on impact of adaptation on the effectiveness and stability of IEAs.

3 Optimal mix and strategic interactions

Adaptation and mitigation have been proposed as complementary instruments in the fight against global warming since the IPCC second assessment report (IPCC 1995). As pointed out in Ingham et al. (2013), complementarity has a more technical meaning in economics than the observation that it should be optimal to use both strategies. In economic terms, one would rather expect mitigation and adaptation to be substitutable strategies, in the sense that the best response to an increase in adaptation would be a decrease in mitigation, and conversely.

Early literature is concerned with the strategic relation between mitigation and adaptation strategies and on their optimal mix. Specifically, many of these early works seek conditions under which adaptation and mitigation could be complementary strategies, where adaptation could possibly lead to a reduction in total emissions, and where carbon leakage could be avoided.

Ingham et al. (2013)

As indicated by the title of the paper, the issue studied in Ingham et al. (2013) is the possibility that adaptation and mitigation be strategic complements. The authors use the MA-model, considering a social planner acting as a single player. They then extend this model to N countries acting either cooperatively or individualistically. Finally, they move to a two-period setting, with a single player (social planner) acting under three scenarios: no uncertainty, mitigation-dependent cost, and endogenous risk. The conclusion from this analysis is that adaptation and mitigation are strategic substitutes in general.

The basic model used in Ingham et al. (2013) is the MA-model for a social planner maximizing the total welfare by choosing total emissions E and adaptation level a. The total welfare is defined as

$$W\left(E, a\right) = B(E) - D(E, a) - \delta C(a),$$

where δ is a parameter that allows to vary the adaptation cost.

Differentiating the FOC yields the following conditions characterizing the impact of a change in the cost of adaptation on the optimal mix (E^*, a^*):

$$\left(B'' - D_{EE}\right)\frac{\partial E^*}{\partial \delta} - D_{Ea}\frac{\partial a^*}{\partial \delta} \quad = \quad 0$$

$$-D_{Ea}\frac{\partial E^*}{\partial\delta}-(D_{aa}+\delta C'')\frac{\partial a^*}{\partial\delta}-C' \quad = \quad 0$$

or, equivalently,

$$\frac{\partial E^*}{\partial\delta} = C'\frac{D_{Ea}}{(D_{EE}-B'')(D_{aa}+\delta C'')-(D_{Ea})^2}<0 \qquad (9)$$

$$\frac{\partial a^*}{\partial\delta} = -C'\frac{D_{EE}}{(D_{EE}-B'')(D_{aa}+\delta C'')-(D_{Ea})^2}<0, \qquad (10)$$

where the denominator corresponds to the determinant of the Hessian matrix of the social planner's optimization problem. Under conditions (2)–(5) and (7), adaptation and mitigation are substitutes: making adaptation more expensive reduces the amount of adaptation and decreases the amount of total pollution, thus resulting in an increase in mitigation.

The authors then move to a setting with multiple countries using either a cooperative or an individualistic behavior, showing that the individualistic (Nash-Cournot) equilibrium will always result in a higher level of emissions and a higher level of adaptation than the cooperative solution. They find that considering multiple countries does not change the finding that adaptation and mitigation are strategic substitutes, which holds for both the cooperative and the individualitic cases. These results are based on assumptions (3)–(5) of the MA-model. It is easy to see using (9)–(10) that allowing the cross-derivative $D_{Ea}=D_{aE}$ to be positive would result in adaptation and mitigation being complementary strategies. As pointed out in Bayramoglu et al. (2018), in the context of adaptation to climate change, the cross-derivative is most likely negative.

The authors then consider a two-period model, where damages $D^2(E,a)$, occurring at the end of the second period, depend on the total emission and adaptation, $E=e^1+e^2$ and $a=a^1+a^2$, and find that their previous conclusions hold, even after introducing uncertainty about the damage cost.

Finally, the authors consider the possibility that the adaptation cost in the second period may depend on the level of mitigation in period 2, $C^2(a^2,e^2)$, assuming that an increase in total emissions increases both the total and marginal cost of adaptation, with

$$C_2^2>0, C_{12}^2>0, C_{22}^2>0.$$

They conclude that the only circumstance where mitigation and adaptation strategies may be complements is where increasing the level of mitigation reduces the future costs of adaptation in a dynamic model.[5]

Ebert & Welsch (2011, 2012)

Ebert & Welsch (2011) introduces a "vulnerability" condition characterizing the slope of a given country's optimal response functions in the MA-model.[6] Since the focus is on a single country, the notation E^* is used to represent the total emissions by all the other countries, dropping the subscript i. Totally differentiating the FOC of an individual country's welfare optimization problem yields the reaction functions

$$R'_{aE} \equiv \frac{da}{dE}=-\frac{D_{Ea}}{D_{aa}+C''}$$

$$R'_{eE^*} \equiv \frac{de}{dE^*}=-\frac{\upsilon}{\upsilon-B''}$$

[5] This last observation is also obtained in Kane & Shogren (2000), where the issue of complementarity / substitutability of adaptation and mitigation is analyzed under an endogenous risk perspective. By assuming that the cost of adaptation depends on the pollution level, the authors show that adaptation and mitigation can be complements or substitutes, depending on the level of risk.

[6] The model in Ebert & Welsch (2011, 2012) uses adaptation expenditures instead of adaptation level as a decision variable. We use the equivalent MA-model that includes an adaptation cost term in the welfare function.

$$R'_{aE^*} \quad \equiv \quad \frac{da_i}{dE^*} = \frac{D_{Ea}B''}{(D_{aa} + C'')\,(\upsilon - B'')},$$

where the quantity

$$\upsilon \equiv D_{EE} - \frac{(D_{Ea})^2}{D_{aa} + C''}$$

is identified by the authors as a measure of *vulnerability* to climate change, increasing with the sensitivity D_{EE} to global pollution and decreasing with the adaptation capacity $\frac{(D_{Ea})^2}{D_{aa}+C''}$.[7] Note that condition (7) is equivalent to

$$B'' < \upsilon.$$

Accordingly, one can check that

- Under condition (5), R'_{aE} is positive, so that adaptation and mitigation measures are strategic substitutes; this result is the same as in Ingham et al. (2013), obtained using a different approach. In both cases, the substitutability of adaptation and mitigation is a direct consequence of condition (5).
- Under condition (7), the slope R'_{aE^*} of the adaptation reaction function is always positive, irrespective of the sign of υ: a decrease in emissions by other countries results in a decrease in own adaptation.[8]
- The slope R'_{eE^*} of the emission reaction function is negative and greater than -1 when the vulnerability parameter $\upsilon > 0$, and is positive when $\upsilon < 0$; this result shows that, when adaptation is available, it is possible to avoid carbon leakage: a decrease in the emissions by other countries can result in a decrease in the emissions of a given country, provided that its vulnerability parameter be negative.

The vulnerability condition appearing in the last result has been used in many subsequent papers to characterize the slope of the emission reaction functions. It is worth noting that a linear or bilinear specification of the damage function results in the vulnerability parameter being negative, and, consequently, in upward-sloping reaction functions in the emission game, while a strictly convex damage function results in the vulnerability parameter being positive, and, consequently, in carbon leakage in the emission game.

The second part of Ebert & Welsch (2011) analyzes the equilibrium solution resulting from countries optimal responses, under a noncooperative scenario in a two-country asymmetrical setting, using a crude approximation of the optimal responses at a given adaptation level, which are assumed linear with constant parameters. In this simplified setting, the authors show that an increase in the vulnerability of any country leads to lower total emissions in equilibrium and provide an intuitive explanation, noting however that this result may not generalize under less restrictive assumption about the optimal response functions. Ebert & Welsch (2012) complements this analysis by characterizing the sensitivity of the equilibrium of the emission/adaptation game to changes in various parameters in the presence of adaptation. To this end, the authors use the welfare function

$$W_i\,(E, a_i) = \eta_i B(E) - D(\gamma_i E, \beta a_i) - C(a_i),$$

where η_i, γ_i and β_i are assumed positive for the first country, and equal to 1 for the second country. A comparative statics analysis is performed in this two-country asymmetric setting, for both cooperative and individualistic behaviors. More precisely, the authors obtain the impact of an increase in productivity (parameter η), pollution sensitivity (γ) and adaptation efficiency (β) on the equilibrium emission and adaptation levels and on individual and total welfare. They find that increases in

[7] Various other quantities have been called “vulnerability” in the climate change literature, for instance an indicator of the impact of climate change on the welfare of countries (IPCC 2007), a decision variable defining the level of environmental damage (Breton & Sbragia 2019), or a parameter of the damage function (Hritonenko & Yatsenko 2016).

[8] Note that, considering individual countries i and j with $i \neq j$, $\frac{\partial a_i}{\partial x_i} = R'_{aE}$ and $\frac{\partial a_i}{\partial x_j} = R'_{aE^*}$ since $\frac{\partial E}{\partial x_i} = \frac{\partial E^*}{\partial x_j} = 1$. The signs of R'_{aE} and R'_{aE^*} thus indicate that, for a given player, adaptation and mitigation are substitute strategies.

productivity and adaptation efficiency lead to an improvement in global welfare only when countries act cooperatively. They also find that the impact of parameters may differ according to the sign of the vulnerability parameter, and that the impacts of productivity and pollution sensitivity are not qualitatively different from what is obtained when adaptation is not available.

To conclude

The findings from these early papers are somewhat disheartening: increasing adaptation results in higher emissions under the realistic assumption that the marginal impact of adaptation decreases with the pollution level ($D_{Ea} < 0$). These works however set the table for further investigation about timing (posterior adaptation where cost decreases with the stock of pollution) and about the form of the damage function, which could result in a negative vulnerability parameter irrespective of the sign of D_{Ea}, leading to a reduction of emissions in response to an increase of emissions by other countries.

4 Timing, commitment, and leadership

The results reported above are all based on a simultaneous solution of the optimality conditions. Clearly, in a game-theoretic context, the solution of an optimization problem involving two decision variables may depend on the sequence of these decisions. Papers investigating the impact of timing can be interpreted as two-stage games, where the stages correspond to the sequence of decisions.

Zehaie (2009)

Zehaie (2009) investigates the impact of the timing of adaptation decisions (prior, simultaneous, or posterior to emission decisions) in a game involving two asymmetric countries. The analysis is performed for three scenarios: a fully cooperative scenario where countries coordinate both their emission and adaptation decisions, a semi-cooperative scenario where they coordinate only their emission decisions, and a noncooperative scenario.

The general model used in Zehaie (2009) can be transformed into a special case of the MA-model, where the specific assumption is that the environmental quality in a given country depends on the sum of two terms. This is equivalent to using the following *additive-argument* specification for the damage function:

$$D_i(E, a_i) \equiv D_i(E - a_i), \quad a_i \leq E \tag{11}$$

In that context, $E - a_i$ is interpreted as country i's *susceptibility* to climate change, where private adaptation can substitute to mitigation to decrease individual environmental damage.

In the fully cooperative scenario, where timing has no impact, examination of the FOC shows that an interior optimal solution is such that the marginal welfare from emissions is higher than that of adaptation: in the first-best solution, mitigation is preferable to adaptation (per unit of substituted emission) because of its public good characteristics. It is worthwhile noting that this result is due to the perfect substitutability of emissions and adaptation in the argument of the damage function.

In the individualistic scenario, assuming an interior solution, the author finds by differentiating the FOC that adaptation has a strategic effect when timed before emission decisions: committing to an irreversible adaptive investment in the first stage changes the second-stage emission game among the two countries, and results in both countries using a higher level of adaptation than in the collectively optimal solution. This strategic effect can be explained by the fact that prior investments in adaptation reduce the individual environmental damage, therefore reducing the domestic need for lowering emissions, thus increasing the total pollution and, hence, the environmental damage to the other country. Irreversible investments in adaptation can then allow a country to transfer some mitigation costs to other countries.

The author also considers a plausible scenario where countries agree to coordinate their emission decisions but decide independently on their private adaptation level. When adaptation is timed before emission decisions, the author finds that the strategic impact of prior adaptation is even higher than in the individualistic scenario, leading to the highest adaptation levels among the three scenarios. This is due to the higher mitigation costs in the second (emissions) stage of the game.

Finally, the case where adaptation decisions are made in the second stage (posterior adaptation) is shown to be equivalent to the simultaneous case in both the noncooperative and semi-cooperative scenarios. When timed simultaneously or after emission decisions, adaptation has no strategic impact, and the equilibrium solution corresponds to that of a static, one-stage game.

As mentioned by the author, the timing of adaptation with respect to mitigation depends on the type of adaptive measures, that is, whether they consist in investments to increase resilience (prior), in corrective measures directly applied to the flow of pollutants (simultaneous), or in remedial measures applied to the damages (posterior). The analysis presented in Zehaie (2009) exploits the optimality conditions in a general model to characterize the reaction functions of countries. This analysis highlights the role of the public/private good characteristics of two substitutable instruments, showing that prior adaptation can be used strategically to modify the emission game, resulting in a higher pollution level than that of the social optimum.

It is worthwhile noting that the substitutive role of emission and adaptation decision variables in the argument of the damage function (11) allows for an intuitive interpretation: adaptation by a country builds private resilience by reducing the impact of environmental damages in the same way as a reduction of the total pollution, but only in the adapting country. It is straightforward to check that an additive-argument form implies that $D_{EE} = D_{aa} = -D_{Ea}$, so that the vulnerability parameter υ defined in Ebert & Welsch (2011) is positive, leading to carbon leakage.

Buob & Stephan (2011)

Buob & Stephan (2011) provides an analysis of posterior adaptation using a dynamic game played over a finite horizon of two periods.[9] The authors argue that their model captures the fact that mitigation requires a long-term perspective, since the benefits of mitigation in the first period only become effective in the second period, whereas adaptation immediately impacts the damage costs of the second period.

The model involves N symmetric countries that maximize the (intertemporal) sum of their utility for consumption and environmental quality under a budget constraint; this model can be expressed as a specific form of the MA-model, where the welfare function of a given country is the weighted sum of the logarithm of linear functions of the emission and adaptation levels (in particular, the argument of the damage function takes the additive form (11)). Emission level decisions in the first period affect the pollution level in the second period and therefore impact the adaptation decisions of the second period (the damage due to pollution in the first period is an exogenous constant). The game is solved by backward induction, under two distinct assumptions about the adaptation cost.

When the cost of adaptation does not depend on the pollution level, adaptation and mitigation are perfect substitutes, given the linearity of the adaptation cost and environmental damage functions; as a result, the authors find that countries will either choose mitigation in the first period or adaptation in the second period, depending on their relative marginal cost. As expected, individual adaptation levels increase with total pollution and initial budget, while emissions decrease with total pollution, initial budget, and number of countries.

When however the marginal cost of adaptation increases with the total pollution level, the authors identify four distinct types of equilibria (no environmental measures, only mitigation, only adaptation,

[9] While sharing the same methodological approach (backward induction) and leading to equivalent equilibrium solutions, this setting is intuitively different from multi-stage games, as in Zehaie (2009), which assume a sequence of decisions in a static context.

and mitigation), depending on the relative values of the (exogenous) initial pollution and budget levels. The results are analytical and regions corresponding to the four types of equilibria are illustrated in the space of initial budget and total pollution, for both the individualistic and the cooperative scenarios, and for various values for the number of countries N.

From this analysis, the authors state various observations on the impact of initial budget (rich or poor countries), total pollution (high or low environmental quality), countries' behavior (cooperative or not), and number of countries, on the willingness to engage into adaptation and/or mitigation activities.

It is worth recalling that other works pointed out that the strategic interaction between adaptation and mitigation may change in a dynamic setting when the cost of adaptation depends on the pollution stock (see, for instance, Kane & Shogren (2000) and Ingham et al. (2013)). Buob & Stephan (2011) however does not address this intertemporal substitutability/complementarity issue, rather focusing on the impact of various parameters on the equilibrium solution.

It easy to check that, when the adaptation cost does not depend on the pollution level, timing has no strategic impact (the solution would be the same if decisions were made simultaneously). Even if the analysis is restricted to a specific form of the basic MA-model, which results in corner solutions, many insights from Buob & Stephan (2011) appear in other specifications of the MA-model in subsequent papers assuming either simultaneous or posterior adaptation.

Eisenack & Kahler (2016)

Eisenack & Kahler (2016) exploits the vulnerability condition of Ebert & Welsch (2011) to show that Stackelberg leadership can lead to Pareto-improving outcomes when countries differ according to the sign of the vulnerability parameter υ.

Since adaptation is a private variable, the authors first introduce the *optimal damage function,* defined by

$$\widetilde{D}(e_i; E_{-i}) = \min_a \left\{ D(E_{-i}, e_i, a) - C(a) \right\},$$

which can be used to reduce the adaptation/emission game to a simpler emission game, where adaptation does not appear, provided adaptation and emission decisions are made simultaneously. In this reduced formulation, the authors show that $\widetilde{D}_{ee} = \upsilon$, which implies that the optimal damage function of a country i with negative (*resp. positive*) vulnerability is concave (*resp. convex*) in e_i.

The authors then investigate the impact of unilateral commitment on the equilibrium solution. They consider two asymmetric countries, possibly differing in the sign of their vulnerability parameter, and investigate the Stackelberg equilibrium corresponding to all possible scenarios on the decisions made in the commitment stage (emissions, adaptation, or both), and on the vulnerability type of the leading player(s). They find that Pareto improvement with respect to the simultaneous Nash equilibrium can occur in various scenarios, notably when the follower exhibits negative vulnerability. Recall that the slope R'_{eE^*} of the reaction function of a country with negative vulnerability is positive: it will decrease its emissions in response to a decrease in the emissions by the other country, which will reduce the need for adaptation in both countries.

Finally, the authors solve a three-stage game where the form of Stackelberg leadership is determined endogenously in the first stage. This first stage is represented by a bi-matrix game, where each country can choose to take the leadership or not in adaptation or emission, leading to four possible strategies for each country and 16 strategy pairs, with corresponding welfare computed from the solution of the Stackelberg games, according to the countries' vulnerability types. The result of this analysis can be summarized as follows:

- If the two countries differ in the sign of their vulnerability parameter, all possible equilibria are such that the country with positive vulnerability takes the lead in at least one variable, while the country with negative vulnerability is always the follower. All equilibria are Pareto-superior in terms of welfare and lead to less adaptation expenditures and less emissions.

- If the vulnerability parameter in the two countries is positive, then no country takes the lead, and the equilibrium corresponds to the noncooperative (Nash) equilibrium solution.
- If the vulnerability parameter in the two countries is negative, then the noncooperative solution is not an equilibrium, and all possible equilibria lead to a Pareto-improvement.

Eisenack and Khaler (2016) provides an interesting contribution by showing that the strategic impact of commitment and leadership in the MA-model can lead to superior equilibrium solutions when the optimized damage function of the follower is concave, or, equivalently, when its vulnerability coefficient υ is negative. Note that this condition may be difficult to observe in practice. As pointed out by the authors, countries with negative vulnerability are characterized by non-trivial, nonconvex damage functions, that is, low values for D_{EE} and/or D_{aa} and a high value for $|D_{Ea}|$.

Breton & Sbragia (2017)

Breton & Sbragia (2017) uses the MAQ-model where countries are assumed symmetric and the damage function is quadratic, taking the additive-argument form

$$D(E,a) = \gamma\,(E-a)^2 \text{ for } e \in [0,1] \text{ and } a < E, \tag{12}$$

where $\gamma > 0$. The authors extend the investigation about commitment and timing of adaptation to a context where n countries are cooperating and m countries are not (partial cooperation), and to a context where the n cooperating countries are Stackelberg leaders in both the adaptation and emission games.

Two timing assumptions for adaptation are considered: prior adaptation relates to countries committing to adaptation measures before deciding about their mitigation levels, either for strategic reasons or because adaptation requires a prior investment; in other cases (simultaneous or posterior adaptation), the authors show that adaptation plays no strategic role, as obtained in Zehaie (2009) for the cooperative and noncooperative cases.

Given the quadratic specification of the welfare function, the authors show that the equilibrium strategies are interior and obtain analytical expressions for the corresponding outcomes in terms of welfare.

Under prior commitment, the findings are:

- When cooperating countries make their decisions simultaneously with individualistic countries, they always adapt more and suffer a lower welfare than the individualistic countries. Depending on the weight γ of the environmental damages, it can happen that cooperating countries mitigate less than the individualistic ones.
- When cooperating countries act as leaders in the adaptation and mitigation games, they always adapt less than individualistic countries. When the number of cooperating countries is small enough, they also mitigate less and achieve a higher welfare.

On the other hand, when adaptation plays no strategic role, the adaptation level is the same for all countries, and the equilibrium results are similar to what is observed in partial cooperation mitigation games:

- When both types of countries make their decision simultaneously, individualistic countries take advantage of the positive externality generated by cooperators and mitigate less, thus suffering a lower environmental cost.
- When cooperating countries act as leaders, if the number of cooperating countries is small enough, both their mitigation levels and their total cost are lower than that of individualistic countries.

The impact of leadership on the global aggregate welfare can be positive or negative, depending on the relative values of δ and γ and on the size of the coalition.

The authors conclude by pointing out that, in all the analyzed scenarios (noncooperation, partial cooperation and leadership), the global aggregate welfare is lower when adaptation measures can be used strategically.

In summary

The four papers surveyed in this section examine the impact of commitment and timing under various perspectives. Eisenack & Kahler (2016) is the only work where the vulnerability parameter v can take negative values; in that case, commitment in the form of Stackelberg leadership in one or both instruments can lead to Pareto improvement when the follower's vulnerability parameter is negative–a case that may be infrequent in practice but has been exploited in many subsequent damage-function models.

The three other works assume that emissions and adaptation are perfect substitutes in the argument of the damage function, which results in a positive vulnerability parameter, and focus on the timing of adaptation decisions. Zehaie (2009) and Breton & Sbragia (2017) find that, when timed before emission decisions, adaptation has a strategic impact that results in a degradation of global welfare, under a wide specter of cooperation and leadership scenarios, while it has no strategic effect if timed simultaneously or after emissions. These results are obtained in a static setting, where the adaptation cost is independent of the global emission level. Buob & Stephan (2011) provides an illustrative example, using a two-period setting, where the relation between adaptation and mitigation may change when the cost of adaptation depends on the emission level from decisions in the first period.

5 Agreements and stability

The issue of self-enforcing agreements and their stability has been extensively discussed in the last three decades, and many papers investigate the impact of adaptation on the size of a stable IEA. The usual setup in that literature is a subdivision of N symmetrical countries into two groups, with n signatory and $m = N - n$ non-signatory countries, where the signatory countries are parties to the agreement (for instance, they agree to act cooperatively by jointly deciding on their emission and/or adaptation levels) and the non-signatory countries adopt an individualistic behavior. The solution of the *membership game* consists of finding a number n^* of signatory countries such that, at n^*, any unilateral deviation from a single country (from signatory to non-signatory or the reverse) would not result in an increase of the welfare of the deviating country.

The main results on the stability of IEAs in the M-model can be summarized in the following way: when the emission levels are determined by a Nash equilibrium between $m+1$ players where the signatories act as a single player, stable coalitions consist of 2 or 3 countries, regardless of N (Carraro & Siniscalco 1993). On the other hand, when the emission levels are the result of a Stackelberg equilibrium where the signatory countries act as leaders, large coalitions, including the grand coalition, can be stable, depending on the cost-benefit ratio of mitigation (Barret 1994). However, these result give rise to the *paradox of cooperation*: in the M-model with leadership, IEAs achieve broad participation when the potential gains from full cooperation are low, so that their overall impact remains limited.

When adaptation is introduced, the sign of the vulnerability parameter v and the timing of adaptation are crucial factors examined in the literature characterizing the stability and size of IEAs. The works reviewed in this section can be classified according to the focus given to one or the other of these two factors. It is worthwhile mentioning that the solution of the membership game cannot be obtained in general without additional assumptions on the form of the benefit, environmental damage, and adaptation cost functions. The papers presented below all assume symmetrical countries and use specific functional forms allowing to obtain numerically the size of a stable coalition for given parameter values.

5.1 Negative vulnerability

The papers presented in this section use specific functional forms where the vulnerability parameter can take negative values. Recall that when $\upsilon < 0$, the damage function is not convex and reaction functions in the emission space are upward sloping.

Bayramoglu et al. (2018)

Bayramoglu et al. (2018) addresses the stability issue by considering a two-stage game, where the first stage is a membership game, and adaptation and mitigation decisions are made simultaneously in the second stage. The second stage is based on the MA-model in which condition (5) is relaxed, allowing for the possibility of mitigation and adaptation to be complementary strategies. Signatory countries agree to coordinate their emission decisions, while non-signatory countries choose their emission levels independently. Recall that, in the MA-model, since adaptation is private, the optimal adaptation level is the same for signatory and non-signatory countries when adaptation and mitigation are decided simultaneously.

In the first part of the paper, the authors consider the second-stage game and obtain the results of Ingham (2013) and Ebert & Welsch (2011) in a setting involving any combinations of n cooperating and m individualistic symmetrical countries, namely, that substitutability vs. complementary of adaptation and mitigation strategies depends on the sign of the cross derivative D_{Ea} and that the slope of the emission reaction functions (with coalitions acting as a single player) depends on the sign of the vulnerability parameter υ. They also derive sufficient conditions for the existence of a unique equilibrium in the second stage and note that these conditions, involving n, B'' and υ, are always satisfied for $\upsilon \geq 0$.

In the second part of the paper, the authors show that $\upsilon \leq 0$ is a sufficient condition for the membership game to be superadditive, providing an incentive for countries to join the coalition of signatories. They argue that upward sloping reaction functions could lead to larger coalitions by reversing the carbon leakage effect where a decrease in the emissions by signatory countries results in an increase in the emissions (and private benefits) of the non-signatories.

This is illustrated by solving the membership game using specific functional forms, that is, the MAQ-model (quadratic benefits and adaptation cost) along with two specifications for the damage function

$$D_1(E,a) = \gamma\,(1 \pm \rho a)\,E - \mu\,(1 \mp \lambda E)\,a \tag{13}$$

$$D_2(E,a) = \gamma E^2 + \rho E - \mu\,(1 \mp \lambda E)\,a, \tag{14}$$

where parameters ρ, γ, λ and μ are positive. In both specifications, the damage function is non convex, and the cross derivatives $D_{Ea} = D_{aE}$ can be positive or negative, according to the $\pm$ choice. For the bilinear damage function D_1, $\upsilon \leq 0$ while for D_2, υ can be negative or positive, depending on the sign of $\lambda^2\mu^2 - 4\gamma\delta$.

Findings are as follows:

- for the damage function D_1, $n^* = 3$ in the M-model (no adaptation) and $n^* \geq 3$ in the MAQ-model, including the grand coalition ($n^* = N$) when υ is sufficiently negative;
- for the damage function D_2, $n^* = 1$ or $n^* = 2$ in the M-model and in the MAQ-model when $\upsilon > 0$. When $\upsilon \leq 0$, $n^* \geq 3$ in the MAQ-model, including the grand coalition when υ is sufficiently negative.

These two examples illustrate that large coalitions can be attained when the vulnerability parameter is sufficiently negative, that is, when the indirect effect of adaptation on environmental damage is sufficiently large to offset the direct effect of emissions, or, equivalently, when the damage function at the optimal adaptation level is sufficiently concave in own emissions.[10]

Finally, the last part of the paper examines the welfare impact of enlarging the size of a coalition of signatories, and more specifically the difference in aggregate welfare between the M- and the MA-models. While increasing the size of the coalition of signatories always results in a decrease in global pollution, this does not necessarily mean an increase in total welfare in the realistic situation where adaptation and mitigation are substitute strategies ($D_{Ea} < 0$). However, if the grand coalition is stable in the MA-model, the solution does correspond to the social optimum and is therefore a better outcome than the equilibrium of the M-model.

The authors conclude that the fear that adaptation will reduce the incentives to mitigate emissions may be unwarranted: adaptation could lead to larger self-enforcing agreements, associated with higher mitigation levels, provided that adaptation changes the slope of the emission reaction functions.

This paper provides a comprehensive analysis of the impact of adaptation on the stability of IEAs in a general setting and interesting insights on the mechanism and consequences of coalition enlargement. Optimistic results can be obtained for the MA-model when the damage function of countries satisfies the Ebert & Welsch (2011) negative vulnerability condition. Examples are provided where the availability of adaptation can even result in the social optimum (stable full cooperation). However, these optimistic results rely on the assumption of symmetric countries with highly negative vulnerability, which may not be realistic, and no intuition is provided about the form of the environmental damage functions or the value of parameters used for the numerical experiments.

Finus et al. (2021)

Finus et al. (2021) analyzes the paradox of cooperation in the MA-model by extending the work in Bayramoglu et al. (2018) to a scenario where the signatory countries coordinate both their emission and adaptation levels and act as leaders in the adaptation/mitigation game.

In the general setting of the MA-model, the authors recall and compare the outcomes, in terms of emissions and welfare, of the Nash-Cournot (NC) and Stackelberg (ST) scenarios, when adaptation and emission levels are chosen simultaneously. Results are obtained from the FOC of the adaptation/mitigation game and differ according to the sign of the vulnerability parameter υ (which characterizes the slope of the emission reaction functions).

Specifically,

- when $\upsilon > 0$, the size of a stable coalition in the ST scenario is at least as large as in the NC scenario, however the welfare of signatory countries is higher, and that of non-signatory countries is lower in the ST than in the NC scenarios;
- when $\upsilon < 0$, the size of a stable coalition is smaller in the ST than in the NC scenario, however the welfare is higher for both signatory and non-signatory countries in the ST scenario.

The authors also compare general properties of coalition formation games (positive externality, superadditivity, cohesiveness) under the NC and the ST scenarios according to the sign of υ, thus providing conjectures on the size and relative efficiency of stable coalitions in the two settings.

In the second part of the paper, the authors analyze the size and efficiency of cooperation using a specific form of the welfare function, namely the MAQ-model with the damage function (14).

[10] Note that the value of the vulnerability parameter can be limited by conditions ensuring the concavity of the individual welfare function and interior solutions.

Results are as follow:

- when $\upsilon > 0$, the size of a stable coalition is at most 2 in the NC scenario, and at least 2 in the ST scenario;
- when $\upsilon < 0$ and $N \geq 7$, $n^* = 3$ is stable in both scenarios. When υ is sufficiently negative, there are two stable coalitions, $n^* = 3$ and $n^* = N$.

To measure the efficiency of stable coalitions and evaluate the "paradox of cooperation," the authors propose two indexes: the importance of cooperation (ICI) is the relative difference between the total welfare under full cooperation (social optimum) and no cooperation (Nash equilibrium), while the improvement over no cooperation (INI) is the relative difference between the total welfare under a stable agreement and no cooperation. The paper reports on an extensive exploration of the parameter space, showing that:

- when $\upsilon > 0$, large coalitions (including the grand coalition) may be stable in the ST scenario, but in that case the ICI and the INI are small. When the ICI is large, only small coalitions are stable and, hence, the INI is small.
- when $\upsilon < 0$ and $D_{Ea} < 0$, in both scenarios, the stable coalition is of size 3 when the ICI is large. A stable grand coalition is only achieved when the ICI is small.

The authors report that the only case where the paradox of cooperation is not confirmed in their numerical experiments happens for some constellations of parameters where the grand coalition is stable, $\upsilon > 0$ and $D_{Ea} < 0$; since this is an unlikely situation, they conclude that the paradox of cooperation introduced in Barret (1994) is not solved by adding (simultaneous) adaptation to the mitigation game, in neither the NC nor the ST scenarios.

This paper complements Bayramoglu et al. (2018), adding the possibility of leadership by the signatory countries, as proposed in Barret (1994). Moreover, while Bayramoglu et al. (2018) showed that large coalitions could be obtained when $\upsilon < 0$, it did not address the efficiency of such coalitions. The numerical experiments performed in Finus et al. (2021) lead to less optimistic conclusions, showing that the availability of adaptation is not likely to result in a significant welfare improvement, even when it allows to enlarge the coalition of signatories.

Barrett (2020)

Barrett (2020) proposes a stylized model where adaptation decisions are made after mitigation decisions, decisions are binary (mitigate or not, adapt or not) and signatories are leaders in the mitigation game. This results in a 4-stage game: membership, mitigation by signatories, mitigation by non-signatories, and adaptation. The agreement consists in signatories coordinating their emission decisions in the second stage. In the fourth stage, all countries make their adaptation decision independently.

The author uses a model with linear emission benefits, linear adaptation costs and bilinear environmental damage costs:

$$W_i\left(e_i, E, a_i\right) = \lambda e_i - \gamma E\left(1 - \beta a_i\right) - \delta a_i$$

where e_i and a_i are binary decision variables and γ, λ and δ are positive parameters.[11] The parameter $\beta \in [0, 1]$ is used to characterize the efficiency of adaptation: when $\beta = 0$, adaptation has no impact on the environmental damage cost, while when $\beta = 1$, adaptation makes the environmental damage cost vanish.

To capture the private- and public-good nature of adaptation and mitigation strategies, the parameter values are assumed to satisfy a set of conditions such that, under the non-cooperative scenario, all countries adapt and none of them abate, while the reverse is true under the full-cooperation scenario.

[11] This simple model assumes that there are only two possible levels of emissions, $\underline{e}$ (mitigate) and $\overline{e}$ (do not mitigate), normalized to take values in $\{0, 1\}$, where $e = 0$ indicates mitigation.

The author then uses this stylized model to characterize stable agreements. Namely, according to the relative value of the adaptation and mitigation costs, the author shows that

- under a stable agreement, either all countries adapt or none adapt, depending on parameter values;
- compared to a scenario where adaptation is not available, the number of participants in stable agreements are never lower, and could be higher, irrespective of whether countries actually adapt in equilibrium.

This paper offers two contrasting scenarios to illustrate the substitutability of adaptation and mitigation measures. The results of the analysis, where all countries choose to either adapt or mitigate, very much depend on the binary nature of the countries' decisions, and the crudeness of the results reflects the simplicity of the underlying model. Still, the paper provides interesting insights on the position of stable partial agreements between the non-cooperative and the cooperative solutions. The membership game is solved analytically, illustrating the role of the relative cost of adaptation and mitigation on the size of stable agreements. It is difficult, however, to clearly discern the role of leadership and of the bilinear nature of the damage function in the stability results.

5.2 Prior adaptation

The papers presented in this section take a different approach, capitalizing on the strategic role of adaptation and on the scope of the cooperation agreements rather than on the slope of the reaction functions in the emission space.

Breton & Sbragia (2019)

Breton & Sbragia (2019) investigates the impact of prior adaptation on the stability of agreements, thereby solving a three-stage game: countries decide on their membership in the first stage, on their adaptation levels in the second stage, and on their emission levels in the third stage.

Three types of agreements (M, A and C) are considered, differing in the scope of cooperation. Under the C-agreement, signatory countries agree to coordinate both their adaptation and mitigation decisions. Under the M-agreement, signatory countries agree to coordinate only their mitigation decisions, while under the A-agreement, signatory countries agree to coordinate only their adaptation decisions.

The corresponding three-stage games are solved under the MAQ-model with an additive-argument damage function (12) and symmetric countries, yielding

$$W_i\left(e_i, E, a_i\right) = e_i\left(2 - e_i\right) - \gamma\left(E - a_i\right)^2 - \delta a_i^2 \text{ for } e_i \in [0,1] \text{ and } a_i < E, \tag{15}$$

where $\gamma > 0$ and $\delta > 0$.[12]

The analysis of the third stage of the game highlights the strategic role of prior adaptation according to the agreement type: the equilibrium emission level in a given country depends on the N-dimensional vector of adaptation levels by all countries: individual emissions increase with own adaptation level while they decrease with the adaptation level of other countries, and the total emission level increases with the adaptation level of either signatory or non-signatory countries. The strategic impact of a given adaptation vector is the same for signatory and non-signatory countries under the A-agreement but differs among the two types of countries under the M- and the C-agreement, where the reaction function of signatory countries to the total emission level E is steeper than that of non-signatory countries.

[12] Recall that under the specification (15), Breton & Sbragia (2017) show that the solution of the FOC in both the adaptation and the emission games are interior.

For the second stage, the authors show that the equilibrium solution of the adaptation game is characterized by the difference in the marginal overall cost of adaptation among signatories (indexed by S) and non-signatories (NS), that is,

$$\Delta = \frac{dW_S}{da_S} - \frac{dW_{NS}}{da_{NS}}, \tag{16}$$

computed at a point where all countries use the same adaptation level. A negative (*resp. positive*) Δ indicate that signatories adapt more (*resp. less*) than non-signatory countries in equilibrium. Accordingly, for the MAQ-model (15), in equilibrium signatory countries adapt more than non-signatory countries under the C- and the M-agreement and adapt less than non-signatory countries under the A-agreement.

For the membership game, analytical results can be derived in the case of the M-agreement while the results under the A- and the C-agreements rely on numerical investigations. The findings are as follows:

- Irrespective of the individual adaptation levels by countries, the maximum size of a M-agreement is 2; at the equilibrium adaptation level, even such a small coalition can only be formed when the benefits of cooperation are small;
- stable coalitions with a sizable number of signatories, up to the grand coalition, can be obtained for the A- and the C-agreement. The equilibrium size n^* of a stable coalition is unique and is increasing with γ and with $\frac{\gamma}{\delta}$.
- while the number of signatory countries of a stable C-agreement is never larger than that of an A-agreement, a C-agreement generally results in better outcomes in terms of total welfare and pollution than an A-agreement;
- C-agreements are not renegotiation-proof (countries may defect after adaptive investments have been realized); however, a C-agreement with defection still results in outcomes that are better than the outcomes of an A-agreement.[13]

The authors report on the benefits of cooperation[14] and the relative position of the equilibrium solution in the range separating the non-cooperative and the cooperative outcomes. They find that, under a C- or an A-agreement, it is possible to approach and even attain the social optimum for some combinations of parameter values, namely when the weight of the environmental damage function is high. Moreover, they obtain that high participation is more likely to happen when the benefits of cooperation are high, showing that the paradox of cooperation does not necessarily hold when countries commit to adaptation measures before deciding on their mitigation levels, and when adaptation is included in the agreement.

This paper offers an alternative optimistic result regarding the impact of adaptation on the stability of IEAs. Recall that under the linear-argument damage specification, the vulnerability parameter is strictly positive. Breton & Sbragia (2019) provides two interesting results in that setting: first, the strategic role of prior adaptation can enhance the stability of IEAs and lead to high cooperation benefits; second, agreements to coordinate only emission levels are not efficient, even in a prior-adaptation setting.

Borrero & Rubio (2022)

Borrero & Rubio (2022) uses the same setting as in Breton & Sbragia (2019): prior adaptation resulting in a three-stage game, and three types of agreements (M, A and C). The authors however use a different

[13] A C-agreement with defection results in players reconsidering their membership decision after adaptation measures have been realized, leading to a coalition of at most two countries in the emission game. This is different from an A-agreement where counties anticipate that there will be no cooperation in the emission stage.

[14] This is defined as the ICI index in Finus et al. (2021).

specification of the damage function,

$$D\,(E,a) = \gamma\,(\rho - a)\,E, \quad a < \rho\beta,$$

where $\gamma > 0$, $\rho > 0$, and $\beta \in (0,1)$. The parameter β is interpreted as the efficiency of adaptation as in Barret (2020) (for $\beta = 1$, adaptation could reduce the damages to 0). This specification of the damage function is a special case of (13) used in Bayramoglu et al. (2018), obtained by setting $\mu = 0$; the damage function is bilinear, making the vulnerability parameter υ negative.

The results obtained by the authors for the three types of agreements are similar and can be summarized by:

- the M- and the C-agreements yield the same results, which are also the same as when adaptation and mitigation are decided simultaneously, and therefore the same as in the bilinear specification in Bayramoglu et al. (2018): for $N \geq 7$, if the efficiency of adaptation β is large enough, the grand coalition is stable, otherwise the stable coalition contains three countries;
- under the A-agreement,
  - non-signatories adapt more, pollute more, and have higher welfare than signatories for all coalition sizes, and these differences increase with the size of the coalition;
  - for $N \geq 11$, if the efficiency of adaptation β is large enough, the grand coalition is stable, otherwise the stable coalition contains six countries.

In both cases, the authors obtain an analytical expression of the minimum adaptation efficiency β required for the grand coalition to be stable and show that this bound converges to one very quickly with N. For instance, they report that for $N = 100$, β should be higher 0.9995 for the M- and C-agreements, and higher than 0.9996 for the A-agreement. The authors conclude that, unless adaptation technology reduces a country's susceptibility to climate change virtually to 0, which is an unrealistic expectation, for all combinations of reasonable parameter values, the only stable agreement contains three (M or C) or six countries (A).

This paper combines the two instruments used in the previous literature (prior adaptation and negative vulnerability) to provide examples where adaptation could enhance the stability of agreements; however, the efficiency of stable coalitions is not directly addressed. The interest of the paper stems from the inclusion of the adaptation efficiency parameter β and the determination of its role on the stability of the grand coalition. Indeed, in the family of models allowing for negative vulnerability, parameter values are constrained by implicit conditions ensuring that (3)-(4) and (7) are satisfied. Here, namely, $a < \rho\beta$ ensures that the damage function is increasing in total emissions. The analysis of the role of the efficiency parameter β on the stability of the grand coalition provides a caveat on the practicality of υ in enhancing coalition stability and efficiency.

Rohrer & Rubio (2024)

Rohrer & Rubio (2024) proposes a multiplicative specification for the damage function in the MA-model:

$$D(E,a) = f(a)h(E), \tag{17}$$

where h is a strictly convex increasing function of total emissions and f is a strictly convex decreasing function of individual adaptation, with $f(0) = 1$ and $f(\infty) = 1 - \beta \in (0,1)$, where β characterizes the efficiency of adaptation. The damage function is further assumed to be strictly convex, which implies that the vulnerability parameter υ is positive. The authors analyze and compare two scenarios about the timing of adaptation with respect to mitigation.

In the first part of the paper, adaptation decisions are made posterior to mitigation decisions. As already shown in the general case, all countries will choose the same adaptation level, so that the only relevant agreement is the M-agreement, where signatory countries coordinate their emission levels.

One can check from the first-order conditions that signatories will emit less than non-signatories and that their welfare will be lower. These results confirm those obtained in Finus et al. (2021), where it is shown that participation in the MA-model with posterior (or simultaneous) adaptation are the same as in the M-model. Using a specific form for the damage function (17), the authors find that, for reasonable parameter values, the maximum size of a stable coalition is 2, provided that the vulnerability parameter value is sufficiently negative.

The second part of the paper considers a prior-adaptation scenario and the three types of agreements (M, A, C); the three-stage game (membership, emissions, adaptation) is solved by backward induction. The authors highlight the strategic role of adaptation in the emission game, which is the same as in the additive-argument setting (12) of Breton & Sbragia (2019):

- Total emissions are increasing with the level of adaptation of any country, in all agreements
- Individual emissions are increasing with own level of adaptation, for all countries, in all agreements
- Individual emissions are decreasing with the level of adaptation of other countries, except when countries are coordinating their emission levels (M- and C-agreements), where individual emissions of signatory countries are increasing with the level of adaptation of other signatory countries.

Examination of the difference Δ defined in Breton & Sbragia (2019) (see Equation (16)) shows that, under the multiplicative specification (17), signatory countries adapt less than non-signatory countries under the A-agreement, and under the M-agreement when participation is high, while signatory countries adapt less than non-signatories under the C-agreement. This result differs from what is obtained in Breton & Sbragia (2019) under the additive-argument specification.

For the membership stage, the authors use the specific form

$$\begin{aligned} h(E) &= E^2 \\ f(a) &= 1-\beta\frac{a}{a+1} \\ W(e,E,a) &= e(2-e)-\gamma\left(1-\beta\frac{a}{a+1}\right)E^2-\delta a. \end{aligned} \tag{18}$$

The solution of the membership game for the specification (18) illustrates how the differences in the strategic role of adaptation according to the agreement scope affect the equilibrium outcome. Results are:

- for the M-agreement, signatory countries adapt more than non signatories when $n > \frac{N-1}{2}$. Timing does not make a significant difference as the size of a stable agreement is $n^* = 2$, as in the simultaneous or posterior adaptation scenarios;
- for the A-agreement, signatory countries adapt less than non signatories. Timing is not significant, as the maximum stable coalition contains $n^* = 3$ countries;
- for the C-agreement, signatory countries always adapt more than non-signatories. Timing is significant, as the grand coalition is the only stable coalition, independently of parameter values.

The authors conclude that the paradox of small coalition does not hold in a MA-model with a multiplicative form in the damage function, if adaptation is decided prior to emissions, and when signatory countries agree to coordinate both their adaptation and their emission decisions. The issue of renegotiation-proofness of a C-agreement is not addressed in the paper.

This paper provides a detailed and comprehensive analysis of the strategic impact of prior adaptation when the damage function takes a multiplicatively separable form. Using a specific instance, it shows that the social optimum can be attained in that case, provided that the countries agree to coordinate both their adaptation and their emission decisions. It is interesting to note that neither the value of the vulnerability parameter υ nor the efficiency of adaptation β play a role in the stability of the agreement under the specification (18).

In summary

The six papers reviewed in this section seek conditions where private adaptation could lead to an improvement in the efficiency of stable environmental agreements. Four of them exploit the vulnerability condition first exposed in Ebert & Welsch (2011), where the availability of adaptation could allow for larger stable coalitions when it modifies the slope of the reaction functions in the emission space. The drawback of this approach in a symmetric setting is that it requires strong assumptions about the environmental damage functions of all countries, namely, as shown in Eisenack & Kahler (2016), that environmental damage at the optimal adaptation level is concave in emissions. As illustrated in Finus et al. (2021), there is no evidence that, for such environmental damage specifications, larger coalitions would result in a significant improvement in welfare. Moreover, as shown in Borrero & Rubio (2022), large stable coalitions in bilinear specifications may require unrealistic assumptions about the efficiency of adaptation.

Three papers exploit the strategic impact of prior adaptation, where countries need to commit to their adaptation levels before deciding about their emission levels. In that case, adaptation may allow for significant improvement in the efficiency and stability of agreements, provided that countries agree to coordinate their adaptation decisions. The three works surveyed in the prior-adaptation section use contrasting specifications for the environmental damage function, illustrating three families of damage models that yield different results: the additive-argument assumption, where the impact of adaptation on damages is similar to that of mitigation, albeit for its private nature; the multiplicative separable assumption, where adaptation rescales the environmental damage function; and the negative vulnerability assumption, where adaptation typically has a linear impact on environmental damages. One general conclusion from reviewing these works is that agreements on adaptation measures that require a prior commitment may be self-enforcing and effective, contrary to agreements on coordinating only mitigation levels.

6 Conclusion

This paper proposes a unified framework to review the literature addressing the repercussions of the availability of private adaptation measures in the mix of instruments to attenuate the negative impacts of climate change.[15] Using a stylized model, it shows how various assumptions about functional forms describing the role of adaptation in reducing damages from total pollution give rise to different conclusions about the impact of adaptation on countries' strategies. Namely, the paper reviews models addressing the complementarity/substitutability of strategies in the adaptation/mitigation and in the mitigation/mitigation spaces, for different sequences in the decision process, and various assumptions about the environmental damage function.

Many aspects remain to be explored in the literature about the optimal mix and the strategic interaction of private adaptation and non-excludable mitigation measures. One obvious direction is to extend models to account for various asymmetries between countries, including the fact that adaptation may not be equally available to all countries. Another is to consider how adaptation could impact agreements of a different nature (e.g. including international trade clauses, club effects, spillovers, punishments, or other-regarding considerations), without necessarily requiring signatories to coordinate their emission levels.

Finally, most models in the adaptation/mitigation literature are static, two-period, or two- to four-stage games. One explanation is that adaptation and mitigation strategies operate in different time scales, at various levels: while adaptation has relatively immediate consequences, the benefits of mitigation will materialize in the long term. On the other hand, mitigation decisions can be implemented

[15] All the works surveyed in this paper differentiate adaptation and mitigation by their private vs. public good characteristics. In reality, adaptation measures could also have non-excludable dimensions (see for instance Masoudi and Zaccour 2017, which considers adaptation spillovers between countries).

in the short term (for instance by reducing or capturing emissions), while adaptation may require sizable investments that degrade with time. For these reasons, adaptation is not necessarily a perfect substitute for mitigation. The extension of the MA-model to a setting allowing for adaptation and pollution stock dynamics, in different time scales, would be an interesting and challenging application of dynamic game theory.

Appendix

A.1 Adaptation definition

The following are excerpts showing the evolution of the definition over time in the IPCC Assessment Reports.

Adaptability: *the degree to which adjustments are possible in practices, processes, or structures of systems to projected or actual changes of climate; adaptation can be spontaneous or planned, and can be carried out in response to or in anticipation of changes in conditions.* (IPCC AR2 1995)

Adaptation: *Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities. Various types of adaptation can be distinguished, including anticipatory and reactive adaptation, private and public adaptation, and autonomous and planned adaptation.* (IPCC AR3 2001 and AR4 2007)

Adaptation: *The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects (Incremental and Transformational adaptation).* (IPCC AR5 2014)

Adaptation: *In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate and its effects.* (IPCC AR6 2023)

A.2 MAQ-model

Let

$$\begin{aligned} B(e) &= e(\eta - e\gamma), \quad 0 \leq e \leq \frac{\eta}{2\gamma^2} \\ C(a) &= \theta a^2 \end{aligned}$$

where $\eta > 0$. B and C are quadratic benefit and adaptation cost functions satisfying conditions (1) and (2), respectively and the individual welfare in a MA-model with quadratic benefit and quadratic adaptation cost is then

$$W(e, E, a) = e(\eta - e\gamma) - D(E, a) - \theta a^2.$$

Set

$$q = 2e\frac{\gamma}{\eta}, \quad 0 \leq q \leq 1.$$

We then have

$$\begin{aligned} W(e, E, a) &= \widetilde{W}(q, Q, r) \\ &= \left(\frac{1}{2}q\frac{\eta}{\gamma}\right)\left(\eta - \frac{1}{2}q\frac{\eta}{\gamma}\gamma\right) - \widetilde{D}(Q, r) - \theta a^2 \\ &= \frac{\eta^2}{4\gamma}q(2-q) - \widetilde{D}(Q, r) - \theta a^2 \end{aligned}$$

yielding the equivalent welfare function

$$\begin{aligned}\widehat{W}\left((q,Q,r)\right) &= \frac{4\gamma}{\eta^2}\widetilde{W}\left(q,Q,r\right)\\ &= q\left(2-q\right)-\frac{4\gamma}{\eta^2}\widetilde{D}\left(Q,r\right)-\frac{4\gamma}{\eta^2}\theta a^2\\ &= q\left(2-q\right)-\widehat{D}\left(Q,r\right)-\delta r^2\end{aligned}$$

with $\delta = \frac{4\gamma\theta}{\eta^2}$.

References

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

[2] Barrett, S. (2020). Dikes versus windmills: Climate treaties and adaptation. Climate Change Economics, 11(04), 2040005.

[3] Bayramoglu, B., Finus, M., & Jacques, J. F. (2018). Climate agreements in a mitigation-adaptation game. Journal of Public Economics, 165, 101–113.

[4] Borrero, M., & Rubio, S. J. (2022). An adaptation-mitigation game: does adaptation promote participation in international environmental agreements?. International Environmental Agreements: Politics, Law and Economics, 22(3), 439–479.

[5] Breton, M., & Sbragia, L. (2017). Adaptation to climate change: commitment and timing issues. Environmental and Resource Economics, 68, 975–995.

[6] Breton, M., & Sbragia, L. (2019). The impact of adaptation on the stability of international environmental agreements. Environmental and Resource Economics, 74, 697–725.

[7] 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.

[8] Carraro, C., & Siniscalco, D. (1993). Strategies for the international protection of the environment. Journal of Public Economics, 52(3), 309–328.

[9] Ebert, U., & Welsch, H. (2011). Optimal response functions in global pollution problems can be upward-sloping: accounting for adaptation. Environmental Economics and Policy Studies, 13, 129–138.

[10] 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, 49–64.

[11] Eisenack, K., & Kähler, L. (2016). Adaptation to climate change can support unilateral emission reductions. Oxford Economic Papers, 68(1), 258–278.

[12] Finus, M., Furini, F., & Rohrer, A. V. (2021). The efficacy of international environmental agreements when adaptation matters: Nash-Cournot vs Stackelberg leadership. Journal of Environmental Economics and Management, 109, 102461.

[13] Hritonenko, N., & Yatsenko, Y. (2016). Mitigation vs. adaptation: analytic models for policy assessment. Environmental Modeling & Assessment, 21(5), 619–627.

[14] Ingham, A., Ma, J., & Ulph, A. M. (2013). Can adaptation and mitigation be complements? Climatic Change, 120, 39–53.

[15] IPCC (2023). Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, 35–115.

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

[17] Masoudi, N., & Zaccour, G. (2018). Adaptation and international environmental agreements. Environmental and Resource Economics, 71, 1–21.

[18] Rohrer, A. V., & Rubio, S. J. (2024). The strategic role of adaptation in international environmental agreements. Journal of Environmental Economics and Management, 124, 102938.

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