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International environmental agreements in the presence of adaptation and self-image

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Abstract : The aim of this paper is to analyze the effect of adaptive investments on international environmental agreements (IEAs) focused on reducing greenhouse gas emissions. It explores the strategic relationships between adaptation and mitigation and their implications for the scope and effectiveness of IEAs. One of the key findings is that adaptation does not improve participation to the agreement. This divergence in results compared to the standard literature stems from a different modelling framework for the terms of the agreement: as in the Paris Agreement, we assume that signatory countries commit to attain a common target, without agreeing to coordinate their actions.

This paper broadens our understanding of how various agreement models can impact efforts to address climate-related challenges.

Keywords : Adaptation, climate change, mitigation, strategy, stability

Résumé : L'objectif de cet article est d'analyser la conséquence de l'utilisation de stratégies d'adaptation sur les accords internationaux pour la protection de l'environnement, notamment pour la réduction des émissions de gaz à effet de serre. L'article explore les relations stratégiques entre l'adaptation et la mitigation et leurs implications pour la portée et l'efficacité des accords environnementaux. L'une des principales conclusions est que l'adaptation n'améliore pas la participation aux accords environnementaux. Cette divergence dans les résultats par rapport à la littérature courante provient d'un cadre de modélisation différent pour les termes de l'accord : comme c'est le cas dans l'Accord de Paris, nous supposons que les pays signataires s'engagent à atteindre un objectif commun, sans accepter de coordonner leurs actions. Ce document élargit notre compréhension de la façon dont divers modèles d'accords environnementaux peuvent influencer les résultats des efforts visant à contrôler les changements climatiques.

Mots clés : Adaptation, mitigation, changement climatique, stabilité, accords environnementaux

1 Introduction

The consequences of climate change are increasingly conspicuous, all over the planet; the number of weather and climate disasters has been constantly increasing, with a special acceleration in the last twenty years. In Europe, the number of climate disasters was 536 in 1999, to rise to 1452 in 2019;[1] in the U.S.A, there were 5.7 confirmed weather/climate disaster events per year between 1990 and 1999, while 28 events were reported in 2023 alone.[2] The European Copernicus system has confirmed 2023 to be the warmest calendar year since global temperature data has been recorded (1850).[3]

According to the 2023 Intergovernmental Panel on Climate Change sixth assessment report (IPCC 2023), several weather extremes and climate change induced by humans are now occurring in every part of the world, with extensive adverse impacts, losses, and damages to nature and people. This will intensify as global warming continues to progress, calling for increasing efforts in both mitigation and adaptation. While climate change mitigation refers to actions or activities that limit emissions of greenhouse gases (GHGs) from entering the atmosphere and/or reduce their levels in the atmosphere, adaptation refers to responses aimed at managing the impacts of climate change. These two kinds of actions have been proposed as complementary strategies in the fight against climate change since the IPCC fourth assessment report (IPCC 2007); however, questions still remain about the relationship between them and about the real impact of adaptation.

The main purpose of this paper is to analyse the impact of countries undertaking adaptive investments, as a response to the repercussions of climate change, on the participation and effectiveness of international environmental agreements (IEAs) aimed at reducing greenhouse gas emissions. This is a critical issue, as policies formulated without accounting for the linkage between adaptation and mitigation could unintentionally undermine the effectiveness of the policies themselves.

Works related to the relationship between adaptation and mitigation include papers investigating the optimal mix between adaptation and mitigation (see, for instance, Kane & Shogren (2000), Zehaie (2009), and Buob & Stephan (2011)). In the specific context of IEAs meant to reduce pollution emissions, the literature is concerned with how the relationship between adaptive investments and mitigation decisions affects the scope and effectiveness of an IEA. This literature can be divided into two groups, according to how the timing of mitigation and adaptation decisions develops.

A first group of papers assumes that investments in adaptive measures are either simultaneous or posterior to mitigation decisions; papers in this group include Marrouch & Ray Chaudhuri (2011), Lazkano et al. (2016), Benchekroun et al. (2017), Bayramoglu et al. (2018), Rubio (2018), Barrett (2020), and Finus et al. (2021), among others. Marrouch & Ray Chaudhuri (2011), in a model where signatory countries act as leaders, show that the greater is the adaptation effectiveness in reducing the marginal damage from total emissions, the larger is the size of the stable coalition of signatories which, in turn, may produce larger welfare. In Bayramoglu et al. (2018), investments in adaptation can make the reaction functions of countries in the mitigation space complementary, which can lead to larger self-enforcing agreements and, in some instances, even to a stable grand coalition. Finus et al. (2021), using the same model as in Bayramoglu et al. (2018), compares the size and the effectiveness of an IEA when signatory and non-signatory countries act simultaneously versus when signatory countries act as leaders. Results differ depending on the sign of the slope of the reaction functions in the mitigation space, which can differ according to adaptation. The overall result of that stream of literature is that, when either full or large participation is reached, cooperation entails small gains, confirming the paradox of cooperation (Barrett, 1994) in a mitigation-adaptation game-theoretic setting.

A second group of papers assumes that investments in adaptive measures are made prior to mitigation decisions. This group includes De Bruin et al. (2011), Breton & Sbragia (2019), Borrero &

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[1] https://www.statista.com/chart/30288/cumulative-number-of-natural-disasters/

[2] https://www.ncei.noaa.gov/access/billions/summary-stats#temporal-comparison-stats

[3] https://climate.copernicus.eu/copernicus-2023-hottest-year-record#:\protect\char126\relax:text=2023%20is%20confirmed%20as%20the,highest%20annual%20value%20in%202016

Rubio (2022), and Roher & Rubio (2024). The general result, common to all the works in that group, is that adaptation can improve participation to an IEA, with positive economic consequences, when adaptation itself is regulated within the IEA. In particular, using a quadratic-damage model, Breton & Sbragia (2019) shows that adaptation has a positive impact in the case of an IEA that regulates only adaptation, as well as in the case of an IEA that regulates both adaptation and mitigation levels, even though this last agreement results to be non-renegotiation proof. Borrero & Rubio (2022), using a linear-damage model, shows that agreements including adaptation can make the grand coalition stable, provided that the effectiveness of adaptation is extremely high, which makes this outcome unrealistic. However, in Rohrer & Rubio (2024), the grand coalition is the unique stable agreement when the agreement involves signatory countries coordinating both their emissions and adaptation decisions.

All the above-mentioned papers share the fundamental setting that the terms of the agreement require signatory countries to coordinate their actions in order to maximize their overall welfare, that is, signatory countries collectively act as a single player (a coalition). However, this setting is fundamentally different from that of the last piece of international legislation on climate change, that is, the current Paris Agreement (2016).

As in the papers of the second group, our paper assumes that adaptive investments are made prior to emissions decisions. Those investments would refer to, for instance, infrastructures for water management (dams, reservoirs, dikes, storm surge barriers) or transportation (ports or bridges), urbanization plans (urban density, parks) and other long-term commitments, mirroring in this way some of the suggestions made by the Working Group II in its sixth assessment report (IPCC 2023). Following Breton & Sbragia (2017, 2019), investments in adaptation reduce countries' vulnerability to climate change, as defined in the last three IPCC assessment reports, so that countries find themselves suffering a lower damage for a given amount of total emissions.

However, differently from the traditional literature on IEA in which the agreement requires signatory countries to form a coalition and function as a unique player, we consider an agreement more in line with some of the main features of the Paris Agreement, where the agreement does not require signatories to coordinate their emission decisions. Indeed, an important characteristic of the Paris Agreement is the signatory countries' freedom of action within an agreement to reach a common temperature target (Article 2). Accordingly, as in Breton & Sbragia (2023), we assume that signatory countries agree on endorsing a common individual emissions target, and then independently choose their adaptation and mitigation levels, in the same way as non-signatory countries. A country's emission target is characterized by the ambition of a pledge with respect to some given reference point – for instance, the EU pledged at Paris to reduce EU emissions by at least 55% with respect to 1990 levels, by 2030.

Furthermore, the Paris Agreement does not involve binding pledges, but it foresees a periodic review process that creates regular moments for naming and shaming strategies to be played by other signatory countries and the civil society against those countries that do not meet their commitments. In our model, this is captured by signatory countries caring for their self-image, which contributes positively ("warm glow") or negatively ("naming and shaming") to their utility, according to where their actions stand compared to the target.[4]

We develop a three-stage game where, in the first stage, countries decide whether to participate to the agreement or not (membership game); in the second stage, countries decide on their adaptation levels (adaptation game); and, finally, in the third stage countries decide on the emission levels maximizing their individual utility, where countries' utility functions differ according to their membership status (signatory or non-signatory).

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[4] "Shaming" strategies against countries that signed the Paris Agreement are on the rise and are frequently deployed by the civil society; see for instance `https://www.reuters.com/sustainability/climate-activists-seek-breakthrough-human-rights-court-ruling-against-european-2024-04-09/`; `https://www.bbc.com/future/article/20231208-the-legal-battles-changing-the-course-of-climate-change`.

In order to appreciate the impact of adaptation on the participation and effectiveness of an IEA in our setting, we develop and analyze three different models. The first model is a benchmark where the IEA requires signatory countries to agree on a common emission target, and where we assume that adaptation measures are not available (BM-model); the second model is built along the same agreement on a common emission target, however allowing both signatory and non-signatory countries to invest in adaptation before deciding on their emissions levels (AM-model); in the third model, we assume that the IEA requires signatory countries to agree on coordinating their adaptation investments, in addition to agreeing on a common emission target (CM-model). This last model is motivated by Articles 6, 7 and 8 of the Paris Agreement, where the possibility of cooperation in adaptation measures is suggested.

As countries are called to increase their efforts in mitigation and adaptation, the first question we address in our paper is about the impact of the ambition of the pledge on the participation and effectiveness of an IEA. In all three models, we find that increasing the ambition level reduces participation, increases total emissions, and decreases global utility. This confirms the results obtained in Breton & Sbragia (2023) in a context without adaptation, that participation is fundamental for the success of an IEA, and that wide and shallow agreements are better than narrow and ambitious ones.

The second question, of obvious interest, concerns the impact of investments in adaptation measures on the stability and effectiveness of IEAs. Comparing the findings of the BM-model with those of the AM-model, our analysis shows that adaptation does not improve participation: moving from a context without adaptation to a context with prior adaptation, participation can either remain at the same level or decrease. In the presence of adaptation, total emissions are higher than in the benchmark case, and this occurs even when participation does not decrease (adaptation is a complement to emissions). Finally, we find that individual and global utilities are higher with adaptation than without. These results suggest that adaptation is beneficial and recommending that countries make adaptive investments as a measure against climate change is a good practice, as this allows them to reach a higher welfare, even if this may induce higher emissions.

The third question investigates the opportunity of regulating adaptation in the agreement. The answer to this question is obtained by comparing the results from the AM-model with those from the CM-model. We find that cooperation in adaptive investments by signatory countries does not have any sizeable impact on participation, but results in lower adaptation levels, which leads to a decrease in total emissions, and an increase in global welfare. We also find that these differences are particularly significant when the level of participation is large.

Finally, the results of our investigations raise a fourth issue, that is, the design of an ideal agreement that maximizes countries' participation and welfare, in a context where signatory countries decide independently on the best way to reach a common emission target.

Our work contributes to the literature on the agreement-emissions-adaptation issues by exploring the potential consequences of adaptation on an alternative type of agreement. In doing this, we broaden our understanding of various agreement models and of their effectiveness for addressing climate-related challenges. Indeed, our model reaches results that are different from those attained in the literature adopting the standard setting where the terms of the IEA consist of forming and acting as a coalition of players; in an individualistic setting where countries care about their public commitments, adaptation does not improve participation, but is however still welfare improving in general.

Our second contribution rests in the development of a theoretical framework for the Paris Agreement, by incorporating some of its key features. Our goal is to gain insights into the potential consequences of such an agreement and to assess whether there are opportunities for improvement. This is an important question, as the Paris Agreement is still the last significant effort to fight climate change. Declared a major success because it was able to reach a near universal participation by countries,[5] nine years after its adoption, its effectiveness seems limited. Indeed, in September 2023, the "Technical

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[5] https://www.un.org/sustainabledevelopment/blog/2016/04/parisagreementsingatures/; https://unfccc.int/process/the-paris-agreement/status-of-ratification

dialogue of the first global stock take"[6] prescribed by the Paris Agreement showed that "much more is needed on all fronts," called for "more ambition" and "urgent actions," and stated that "the world is not on track to meet the long-term goals of the Paris Agreement."

The paper is organized as follows. Section 2 presents the model and notation. The solution of the game corresponding the BM, AM and CM models is obtained by backward induction in Sections 3 (emissions), 4 (adaptation) and 5 (membership). Section 6 presents and discusses the results, and Section 7 is a short conclusion. Auxiliary developments can be found in the Appendix (Section A1).

2 Model

We consider N symmetric countries whose production activity creates economic value but also pollution emissions as a by-product. We assume that the emissions generated by country i are proportional to its production level, and we denote them by $x_i \geq 0$. The net revenue derived from country i's production activity is a quadratic function with 0 intercept. We normalize the emissions units so that emissions are equal to 1 at the production level that maximizes revenue (BAU), and we normalize the monetary units so that the BAU revenue is equal to $\frac{1}{2}$. The net revenue of country i is then given by

$$R_i(x_i) = \left(1 - \frac{1}{2}x_i\right) x_i.$$

The environmental damage suffered by countries as a consequence of the global production activity is related to the total emissions

$$E = \sum_{i=1}^{N} x_i,$$

as well as to their level of adaptation. Adaptation is a private good that reduces the *vulnerability* of country i, that is, the negative consequences of the global emissions E for this country. Denote by a_i the adaptation level of a given country i and by

$$v_i \equiv \frac{E}{N} - a_i$$

country i's vulnerability to global pollution after it has built some resilience to climate change. The environmental damage function of country i is then given by

$$D_i(E, v_i) = d_1 v_i + d_2 v_i^2, \tag{1}$$

where $0 \leq d_1 < 1$ and $d_2 > 0$.[7]

The cost of adaptive investments is increasing and convex in the level of adaptation and is given by

$$C_i(a_i) = \frac{c}{2} a_i^2,$$

where c is a positive parameter, common to all countries. We assume that the parameter c is sufficiently high, so that vulnerability stays positive for the optimal level of adaptation chosen by a country (see Appendix A1.2).

Under these assumptions, the environmental damage function satisfies all the standard properties sought in the IEA literature:[8]

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[6] `https://unfccc.int/documents/631600`

[7] When $d_1 \geq 1$, revenue from production cannot exceed damage in the symmetric base case (see Appendix A1.1).

[8] See, for instance, Ebert & Welsch (2012) and Ingham et al. (2013). This damage function generalizes the one used in Breton and Sbragia (2019).

- Increasing in total emissions, decreasing in adaptation

$$\begin{aligned}\frac{\partial D_i}{\partial E} &= \frac{d_1}{N} + 2\frac{d_2}{N}\left(\frac{E}{N} - a_i\right) > 0\\ \frac{\partial D_i}{\partial a_i} &= -2d_2\left(\frac{E}{N} - a_i\right) - d_1 < 0;\end{aligned}$$

- Convex

$$\begin{aligned}\frac{\partial^2 D_i}{\partial E^2} &= \frac{2}{N^2}d_2 > 0\\ \frac{\partial^2 D_i}{\partial a_i^2} &= 2d_2 > 0\\ \left(\frac{\partial^2 D_i}{\partial E^2}\right)\left(\frac{\partial^2 D_i}{\partial a_i^2}\right) - \left(\frac{\partial^2 D_i}{\partial E \partial a_i}\right)^2 &= 0\end{aligned}$$

- Decreasing marginal impact of adaptation w.r.t. total emissions.

$$\frac{\partial^2 D_i}{\partial E \partial a_i} = -\frac{2}{N}d_2 < 0.$$

Note that when no country invests in adaption, we retrieve the conventional increasing quadratic damage function of the total emissions, equally suffered by all countries:

$$D(E) = \frac{d_1}{N}E + \frac{d_2}{N^2}E^2.$$

We partition the set of countries into two groups, where “signatory” countries (indexed by S) agree to participate in the agreement and “non-signatory” countries (indexed by NS) do not, and we denote by n (*resp.* m) the number of signatory (*resp. non-signatory*) countries, with $n + m = N$.

Inspired by the agreed common temperature target of the Paris Agreement and, as in Breton and Sbragia (2023), we assume that signatory countries agree on some common emissions target. Furthermore, given the non-legally binding nature of the pledges, we assume a periodic review process, as in the Paris Agreement, that allows for “naming and shaming” strategies to be deployed by countries and stakeholders.

Accordingly, we assume that signatory countries develop a sense of responsibility towards their public commitment (a *self-image)* as their actions are measured against the target, at both the international and national levels. We model the self-image as a linear function of the deviation of the country’s emissions level from the agreed target. More specifically, the self-image S_i is positive (*resp. negative*) if a signatory country i overcomplies (*resp. undercomplies*) with respect to the common target, giving rise to a sense of pride (*resp. sense of shame*) that contributes to its utility. Let $T \equiv \frac{r}{\alpha}$ denote the agreed common target, where r is an arbitrary reference point[9] and α is the ambition of the pledge, used as a design parameter that is inversely related to the target (since we are considering a public bad, more ambitious pledges correspond to lower emission targets). The self-image function of a signatory country i is then given by

$$S_i\left(x_i; T\right) = T - x_i.$$

We further assume that the relative weight of the self-image in the utility function of signatory countries depends on the seriousness of the global environmental problem, proxied by the average total emissions $\frac{E}{N}$, on countries concern about climate change, represented by a parameter γ, and on the ambition

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[9] e.g. emission of a given past year

of the signatories' commitment α, so that the utility of signatory countries includes an additional self-image component equal to

$$\delta \frac{E}{N}\left(T - x_i\right),$$

where $\delta = \gamma\alpha$.

Finally, since the agreement is about reaching a common target, and not coordinating emissions, signatory countries choose their emissions levels by independently maximizing their individual utility, in the same way as non-signatory countries. The fundamental difference between a signatory and non-signatory country lies in their utility functions, where only signatory countries derive utility from their compliance or non-compliance to the agreement.

In the sequel, to simplify the exposition, we denote the emission and adaptation decisions of a signatory country (indexed by i) by the pair (x_i, a_i) and that of a non-signatory country (indexed by j) by the pair (y_j, b_j). The utility functions of a non-signatory country j and a signatory country i are then, respectively,

$$\begin{aligned}
U_j^{NS} &= \left(1 - \frac{y_j}{2}\right) y_j - d_1 \left(\frac{E}{N} - b_j\right) - d_2 \left(\frac{E}{N} - b_j\right)^2 - \frac{c}{2} b_j^2 \\
U_i^{S} &= \left(1 - \frac{x_i}{2}\right) x_i - d_1 \left(\frac{E}{N} - a_i\right) - d_2 \left(\frac{E}{N} - a_i\right)^2 - \frac{c}{2} a_i^2 + \delta \frac{E}{N}\left(T - x_i\right).
\end{aligned}$$

We now proceed to obtain the mitigation and adaptation levels of countries in this context by soving a sequential three-stage game. In the first stage (membership game), countries decide on their membership status, yielding the number n of signatory countries. In the second stage (adaptation game), signatory and non-signatory countries decide on their adaptation levels $a_i, i = 1, ..., n$ and $b_j, j = 1, ..., m$. In the third stage (emission game), countries independently decide on their emission levels, given the adaptation investments already in place. The game is solved by backward induction in the following sections.

3 Emissions game

In this section, we solve the emissions game among the $N = n + m$ countries in a general setting where the adaptation levels have already been decided and the investment committed in a previous stage. This general setting does not assume that countries coordinate their adaptation decisions in any way, or that countries in a given subset use the same level of adaptation. Moreover, according to our assumptions about the terms of the agreement, both signatory and non-signatory countries choose their emission levels independently.

3.1 General case

The optimisation problem of a representative non-signatory country j is given by

$$\max_{y_j \geq 0} \left\{ U_j^{NS} = \left(1 - \frac{y_j}{2}\right) y_j - d_1 \left(\frac{E}{N} - b_j\right) - d_2 \left(\frac{E}{N} - b_j\right)^2 - \frac{c}{2} b_j^2 \right\}, \tag{2}$$

while the optimisation problem of a representative signatory country i is

$$\max_{x_i \geq 0} \left\{ U_i^{S} = \left(1 - \frac{x_i}{2}\right) x_i - d_1 \left(\frac{E}{N} - a_i\right) - d_2 \left(\frac{E}{N} - a_i\right)^2 - \frac{c}{2} a_i^2 + \delta \frac{E}{N}\left(T - x_i\right) \right\}. \tag{3}$$

Assuming an interior solution, the first order condition for the problem of a non-signatory country is

$$\frac{d}{dy_j} \left(\left(1 - \frac{y_j}{2}\right) y_j - d_1 \left(\frac{O_j + y_j}{N} - b_j\right) - d_2 \left(\frac{O_j + y_j}{N} - b_j\right)^2 - \frac{c}{2} b_j^2 \right) = 0,$$

where $O_j = E - y_j$.

It is straightforward to check that U_j^{NS} is strictly concave in y_j,

$$\frac{d^2 U_j^{NS}}{dy_j^2} = -\frac{2d_2 + N^2}{N^2} < 0.$$

Solving the first order condition yields the optimal emission as a function of E and b_j

$$y_j\left(E, b_j\right) = \frac{N - d_1}{N} + \frac{2d_2}{N} b_j - \frac{2d_2}{N^2} E,$$

from which we compute the total emissions of non-signatory countries

$$\sum_{j=1}^{m} y_j = m\frac{N - d_1}{N} + m\frac{2d_2}{N}\overline{b} - m\frac{2d_2}{N^2}E,$$

where $\overline{b} = \frac{\sum_{j=1}^{m} b_j}{m}$ is the average adaptation by all the non-signatory countries.

Similarly, assuming an interior solution, the first order condition for the optimisation problem of a representative signatory country is

$$\frac{d}{dx_i}\left(\left(1 - \frac{x_i}{2}\right)x_i - d_1\left(\frac{O_i + x_i}{N} - a_i\right) - d_2\left(\frac{O_i + x_i}{N} - a_i\right)^2 - \frac{c}{2}a_i^2 + \left(\frac{O_i + x_i}{N}\right)\delta\left(T - x_i\right)\right) = 0,$$

where $O_i = E - x_i$.

The function U_i^S is strictly concave in x_i

$$\frac{d^2 U_i^S}{dx_i^2} = -\frac{N^2 + 2\delta N + 2d_2}{N^2} < 0,$$

and solving for the first order condition yields the optimal emission as a function of E and a_i:

$$x_i\left(E, a_i\right) = \frac{N - d_1 + T\delta}{N + \delta} + 2\frac{d_2}{N + \delta}a_i - \frac{2d_2 + N\delta}{N\left(N + \delta\right)}E,$$

from which we compute the total emissions of signatory countries

$$\sum_{i=1}^{n} x_i = n\frac{N - d_1 + T\delta}{N + \delta} + n\frac{2d_2}{N + \delta}\overline{a} - n\frac{2d_2 + N\delta}{N\left(N + \delta\right)}E,$$

where $\overline{a} = \frac{\sum_{i=1}^{n} a_i}{n}$ is the average adaptation by signatory countries.

We now obtain the total emissions by all countries at equilibrium as a function of the average adaptation in each group:

$$\begin{aligned} E\left(\overline{a}, \overline{b}\right) &= \sum_{i=1}^{n} x_i + \sum_{i=1}^{m} y_i \\ &= Q_1 + Q_2\overline{b} + Q_3\overline{a} \end{aligned} \tag{4}$$

where

$$\begin{aligned} Q_1 &= \frac{N\left(\left(m\delta + N^2\right)\left(N - d_1\right) + NTn\delta\right)}{H} > 0 \\ Q_2 &= \frac{2md_2N\left(N + \delta\right)}{H} > 0 \\ Q_3 &= \frac{2N^2nd_2}{H} > 0 \\ H &= N^2\left(N + \delta\left(n + 1\right)\right) + 2d_2\left(m\delta + N^2\right) > 0. \end{aligned}$$

Note that the total emissions at equilibrium is a linear increasing function of the average adaptation levels of signatory and non-signatory countries.

Replacing E by its expression (4) in the optimal emissions of individual countries, we obtain the emission reaction of non-signatory and signatory countries to the adaptation of all players, that is, own adaptation, total adaptation by the countries in the same group and by the countries in the other group.

For a given non-signatory country j, let B_j represent the total adaptation by all non-signatory countries except j. Using $\overline{b} = \frac{b_j + B_j}{m}$, we obtain

$$y_j\left(b_j, B_j, \overline{a}\right) = D_1 + D_2 b_j + D_3 B_j + D_4 \overline{a}, \tag{5}$$

where

$$\begin{aligned} D_1 &= \frac{N\left(N-d_1\right)\left(N+\delta\left(n+1\right)\right) - 2Tn\delta d_2}{H} \\ D_2 &= 2d_2 \frac{2d_2\left(N\left(N-1\right)+\delta\left(m-1\right)\right) + N^2\left(N+\delta\left(n+1\right)\right)}{NH} > 0 \\ D_3 &= -4d_2^2 \frac{N+\delta}{HN} < 0 \\ D_4 &= -4d_2^2 \frac{n}{H} < 0. \end{aligned}$$

At equilibrium, the emissions of a non-signatory country are increasing in its own adaptation level (strategic complements) and decreasing in the other countries adaptation levels (strategic substitutes). It is also interesting to note that the emissions of a non-signatory country are decreasing in the target T of the signatory countries at equilibrium: when signatory countries are less ambitious and agree on a higher target emission level, non-signatory countries reduce their emissions in order to mitigate their damage cost.

In the same way, using $\overline{a} = \frac{a_i + A_i}{n}$, where A_i represent the total adaptation by all signatory countries except i, a signatory country's emission reaction to the adaptation $\left(a_i, A_i, \overline{b}\right)$ by all countries is given by

$$x_i\left(a_i, A_i, \overline{b}\right) = S_1 + S_2 a_i + S_3 A_i + S_4 \overline{b} \tag{6}$$

where

$$\begin{aligned} S_1 &= \frac{N\left(N-d_1\right)\left(N-\delta m\right) + T\delta\left(2d_2 m + N^2\right)}{H} \\ S_2 &= 2d_2 \frac{2d_2\left(N\left(N-1\right)+m\delta\right) + N^2\left(N+n\delta\right)}{\left(N+\delta\right)H} > 0 \\ S_3 &= -2Nd_2 \frac{2d_2 + N\delta}{H\left(N+\delta\right)} < 0 \\ S_4 &= -2md_2 \frac{2d_2 + N\delta}{H} < 0. \end{aligned}$$

Again, emissions by a signatory country are increasing in its own adaptation level (strategic complements) and decreasing in the adaptation levels of the other countries (strategic substitutes).

3.2 Special cases

3.2.1 BM-model

In the BM-model, which serves as a comparative benchmark to analyze the impact of adaptation on the stability and outcomes of IEAs, countries do not invest in adaptation. The solution of the emission game in this case is readily obtained by setting adaptation levels to 0 in the general model, yielding

$$y_j = \frac{N\left(N-d_1\right)\left(N+\delta\left(n+1\right)\right)-2Tn\delta d_2}{H} \tag{7}$$

$$x_i = \frac{N\left(N-d_1\right)\left(N-\delta m\right)+T\delta\left(2d_2m+N^2\right)}{H}. \tag{8}$$

In that case, it is straightforward to show (see Appendix A1.3) that total emissions are decreasing with the participation to the agreement (n), while individual emissions from both groups of countries are increasing with n.

3.2.2 Group-specific adaptation

While the general model makes no specific assumption about the adaptation levels used by the countries, if countries in a given group were to use the same level of adaptation, that is, b for non-signatory and a for signatory countries, the equilibrium emission levels of signatory and non-signatory countries are obtained by setting $a_i = a$, $A_i = (n-1)a$, $b_j = b$, and $B_j = (m-1)b$, yielding

$$y_j\left(a,b\right) = D_1 + D_4a + D_5b \tag{9}$$

$$x_i\left(a,b\right) = S_1 + S_4b + S_5a \tag{10}$$

where

$$\begin{aligned} D_5 &= D_2 + \left(m-1\right)D_3 \\ &= 2d_2\frac{N\left(N+\delta\left(n+1\right)\right)+2nd_2}{H} > 0 \\ S_5 &= S_2 + \left(n-1\right)S_3 \\ &= 2d_2\frac{N^2+2md_2}{H} > 0. \end{aligned}$$

This shows that, when all countries in a group use identical adaptation levels, individual emissions in one group are increasing in own adaptation and decreasing in the other group's adaptation level.

4 Adaptation game

We now solve the second stage of the game, using backward induction to determine the equilibrium adaptation levels of signatory and non-signatory countries for a given n, assuming that the equilibrium solution to the emission game is interior. To alleviate notation, we use the fact that the equilibrium emission strategies and the total emissions are linear functions of the adaptation variables, using Equations (4), (5) and (6).

4.1 Non-signatory countries

In the second stage, a representative non-signatory country j solves

$$\max_{b_j\geq 0}\left\{U_j^{NS} = \left(1-\frac{y_j}{2}\right)y_j - d_1\left(\frac{E}{N}-b_j\right) - d_2\left(\frac{E}{N}-b_j\right)^2 - \frac{c}{2}b_j^2\right\},$$

taking into account the equilibrium total and individual emissions as a function of its adaptation level, that is, Equations (4) and (5) with $\overline{b} = \frac{b_j+B_j}{m}$.

Assuming an interior solution, the first order condition for the non-signatory country j is then

$$\frac{d}{db_j}\begin{pmatrix} \left(1-\frac{D_1+D_2b_j+D_3B_j+D_4\overline{a}}{2}\right)\left(D_1+D_2b_j+D_3B_j+D_4\overline{a}\right) \\ -d_1\left(\frac{Q_1+Q_2\frac{b_j+B_j}{m}+Q_3\overline{a}}{N}-b_j\right) - d_2\left(\frac{Q_1+Q_2\frac{b_j+B_j}{m}+Q_3\overline{a}}{N}-b_j\right)^2 - \frac{c}{2}b_j^2 \end{pmatrix} = 0.$$

It is straightforward to check that U_j^{NS} is strictly concave in its own adaptation:

$$\frac{d^2 U_j^{NS}}{db_j^2} = -2d_2 \frac{\left(-Q_2 + Nm\right)^2}{N^2 m^2} - \left(c + D_2^2\right) < 0.$$

Given that non-signatory countries are symmetric, one can set $b_j = b$ and $B_j = (m-1)\,b$ in the first order condition, which reduces to a linear function of b and $\overline{a}$

$$\begin{aligned} b\left(2d_2\left(N - Q_2\right)\frac{Q_2 - Nm}{N^2 m} - c - D_2\left(D_2 + D_3\left(m-1\right)\right)\right) \\ + \overline{a}\left(2d_2 Q_3 \frac{-Q_2 + Nm}{N^2 m} - D_2 D_4\right) \\ + \left(-Q_2 + Nm\right)\frac{Nd_1 + 2Q_1 d_2}{N^2 m} - D_2\left(D_1 - 1\right) = 0, \end{aligned} \quad (11)$$

yielding the reaction function

$$b(\overline{a}) = \frac{C_1 + G_1 \overline{a}}{F_1} \quad (12)$$

where

$$\begin{aligned} F_1 &= c + 2H_1 d_2\left(2d_2 + N^4 m\right)\frac{K + 2Nnd_2}{H^2 N^2} > 0 \\ G_1 &= 4nH_1 d_2^2 \frac{2d_2 + N^4 m}{H^2 N} > 0 \\ C_1 &= H_1\left(2d_2 + N^2\right)\frac{NL + Kd_1 + 2NTn\delta d_2}{H^2 N^2} > 0 \end{aligned}$$

with

$$\begin{aligned} K &= N^2\left(N + \delta\left(n+1\right)\right) \\ L &= 2d_2\left(N^2 + m\delta\right) \\ L_1 &= 2d_2\left(N\left(N-1\right) + \delta\left(m-1\right)\right) \\ H &= K + L \\ H_1 &= K + L_1. \end{aligned}$$

The solution of the adaptation game shows that, at equilibrium, non-signatory countries' adaptation level is increasing with the adaptation level of the signatory countries (strategic complements).

4.2 Signatory countries

For the signatory countries, we consider two distinct scenarios. In the first scenario (AM-model), signatory countries make their adaptation decisions individually, while in the second scenario, (CM-model), the terms of the agreement requires signatory countries to coordinate their adaptation decisions in order to maximize their joint utility.

4.2.1 AM-model

In the AM-model, signatory countries choose their adaptation level independently. Accordingly, at the beginning of the second stage, a representative signatory country i solves

$$\max_{a_i \geq 0}\left\{U_i^S = \left(1 - \frac{x_i}{2}\right)x_i - d_1\left(\frac{E}{N} - a_i\right) - d_2\left(\frac{E}{N} - a_i\right)^2 - \frac{c}{2}a_i^2 + \delta\frac{E}{N}\left(T - x_i\right)\right\},$$

taking into account the equilibrium total and individual emissions as a function of its adaptation level, that is, Equations (4) and (6) with $\overline{a} = \frac{a_i + A_i}{n}$.

Assuming an interior solution, the first order condition for a signatory country is then

$$\frac{d}{da_i}\left(\begin{array}{c} \left(1-\frac{S_1+S_2a_i+S_3A_i+S_4\bar{b}}{2}\right)\left(S_1+S_2a_i+S_3A_i+S_4\bar{b}\right) \\ -d_1\left(\frac{Q_1+Q_2\bar{b}+Q_3\frac{a_i+A_i}{n}}{N}-a_i\right)-d_2\left(\frac{Q_1+Q_2\bar{b}+Q_3\frac{a_i+A_i}{n}}{N}-a_i\right)^2 \\ -\frac{c}{2}a_i^2+\left(\frac{Q_1+Q_2\bar{b}+Q_3\frac{a_i+A_i}{n}}{N}\right)\delta\left(T-\left(S_1+S_2a_i+S_3A_i+S_4\bar{b}\right)\right) \end{array}\right)=0.$$

The second derivative is

$$\frac{d^2U_i^S}{da_i^2}=-\frac{2d_2\left(-Q_3+Nn\right)^2}{N^2n^2}-S_2^2-c-2\delta Q_3\frac{S_2}{Nn},$$

where

$$\begin{aligned} Q_3 &= N\frac{2Nnd_2}{H}>0 \\ S_2 &= \frac{2d_2\left(2d_2\left(N\left(N-1\right)+m\delta\right)+N^2\left(N+n\delta\right)\right)}{\left(N+\delta\right)H}>0, \end{aligned}$$

and it is easy to check that the utility function of a signatory country is stictly concave in its own adaptation level.

Given that signatory countries are symmetric, $a_i=a$ and $A_i=\left(n-1\right)a$, and the first-order condition reduces to a linear function of a and $\bar{b}$, yielding the reaction function

$$a\left(\bar{b}\right)=\frac{C_2+G_2\bar{b}}{F_2} \tag{13}$$

where

$$\begin{aligned} F_2 =& c+2N^2nd_2\left(K_2+N^2\delta+2md_2\left(N+\delta\right)\right)\frac{N^2\delta+H_2}{H^2} \\ &+4d_2^2\frac{\left(2md_2+N^2\right)\left(H_2+N\delta\left(N+\delta\right)\right)+Nn\delta H_2}{H^2\left(N+\delta\right)}>0 \\ G_2 =& \frac{4md_2^2\left(2d_2+N\left(N+2\delta\right)\right)\left(H_2+N\delta\left(N+\delta\right)\right)}{H^2\left(N+\delta\right)}>0 \\ C_2 =& d_1\frac{2H_2+N^2\delta}{H}+2d_2\frac{HH_2+\left(N\left(N-1\right)+2m\delta\right)N\left(N-d_1\right)\left(H_2+N\delta\left(N+\delta\right)\right)}{H^2\left(N+\delta\right)} \\ &+2T\delta d_2\frac{H_2\left(N^2\left(n-1\right)-2md_2\right)+N^3\left(N+\delta\right)\left(N+2\left(d_2+n\delta\right)\right)}{H^2\left(N+\delta\right)}, \end{aligned}$$

with

$$\begin{aligned} K_2 &= N^2\left(N+n\delta\right)>0 \\ L_2 &= 2d_2\left(N\left(N-1\right)+m\delta\right)>0 \\ H_2 &= K_2+L_2. \end{aligned}$$

Note that the reaction function (13) shows that the adaptation of signatory and non-signatory countries are strategic complements in the AM-model ($G_2>0$).

The equilibrium of the adaptation game in the AM-model is obtained by solving the system of linear reaction functions

$$\left\{\begin{array}{l} b=\frac{C_1+G_1a}{F_1} \\ a=\frac{C_2+G_2b}{F_2}, \end{array}\right.$$

yielding

$$b^{AM} = \frac{G_1C_2 + C_1F_2}{F_1F_2 - G_1G_2} \tag{14}$$

$$a^{AM} = \frac{G_2C_1 + C_2F_1}{F_1F_2 - G_1G_2}. \tag{15}$$

4.2.2 CM-model

In the CM-model, we assume that signatory countries coordinate their adaptation decision, and we denote by a their collective adaptation level. The resulting equilibrium emissions from signatory countries is obtained from Equation (6) by setting $a_i = a$ and $A_i = (n-1)\,a$, yielding

$$\begin{aligned} x_i\left(a, \bar{b}\right) &= S_1 + \left(S_2 + S_3\left(n-1\right)\right) a + S_4\bar{b} \\ &= S_1 + S_5 a + S_4 \bar{b}. \end{aligned} \tag{16}$$

In that case, the signatory countries solve

$$\max_{a \geq 0} \left\{ U_i^S = \left(1 - \frac{x_i}{2}\right) x_i - d_1\left(\frac{E}{N} - a\right) - d_2\left(\frac{E}{N} - a\right)^2 - \frac{c}{2}a^2 + \delta\frac{E}{N}\left(T - x_i\right) \right\},$$

using the reaction functions (16) and (4). Assuming an interior solution, the first order condition for the joint adaptation problem of the signatory countries is then

$$\frac{d}{da}\left(\begin{array}{c} \left(1 - \frac{S_1 + S_5 a + S_4\bar{b}}{2}\right)\left(S_1 + S_5 a + S_4\bar{b}\right) \\ -d_1\left(\frac{Q_1 + Q_2\bar{b} + Q_3 a}{N} - a\right) - d_2\left(\frac{Q_1 + Q_2\bar{b} + Q_3 a}{N} - a\right)^2 - \frac{c}{2}a^2 \\ + \left(\frac{Q_1 + Q_2\bar{b} + Q_3 a}{N}\right)\delta\left(T - \left(S_1 + S_5 a + S_4\bar{b}\right)\right) \end{array} \right) = 0.$$

The second derivative is

$$\frac{d^2U_i^S}{da^2} = -\frac{2d_2\left(N - Q_3\right)^2}{N^2} - \left(S_5^2 + c\right) - \frac{2\delta Q_3 S_5}{N},$$

where

$$S_5 = 2d_2\frac{N^2\left(N + \delta\right) + 2d_2\left(m\delta + Nm\right)}{H\left(N + \delta\right)} > 0$$

and the utility function of signatory countries is stictly concave in the joint adaptation level.

The first order condition yields the linear reaction function

$$a\left(\bar{b}\right) = \frac{C_3 + G_3\bar{b}}{F_3}, \tag{17}$$

where

$$\begin{aligned} F_3 =& c + 2d_2\frac{\left(K + 2mN_1d_2\right)^2}{H^2} + 4d_2^2\left(2md_2 + N^2\right)\frac{2md_2 + N^2 + 2Nn\delta}{H^2} > 0 \\ G_3 =& 4md_2^2\frac{N^2\left(N + 2\delta\right)\left(N + n\delta\right) + 2d_2\left(2md_2 + N\left(N\left(m+1\right) + \delta\left(2m + n\right)\right)\right)}{H^2} > 0 \\ C_3 =& \frac{T\delta d_2}{H^2}\left(4md_2\left(N\left(N\left(n-2\right) - n\delta\right) - 2md_2\right) + 2N\left(N^2\left(N\left(2n-1\right) + 2n^2\delta\right) + 2nd_2\left(m\delta + N^2\right)\right)\right) \\ & + d_1\frac{N^2\left(N + \delta\left(n+1\right)\right) + 2md_2\left(N + \delta\right)}{H} \\ & + 2d_2\left(\frac{2md_2 + N^2}{H} + N\left(N - d_1\right)\frac{\left(N\left(N-1\right) + 2m\delta\right)\left(N\left(N + n\delta\right) + 2md_2\right)}{H^2}\right). \end{aligned}$$

When the signatory countries coordinate their adaptation decisions, the reaction function (17) shows that the adaptation of signatory and non-signatory countries are strategic complements ($G_3 > 0$), as in the AM-model.

The equilibrium of the adaptation game in the CM-model is obtained by solving the system of linear reaction functions

$$\begin{cases} b = \frac{C_1 + G_1 a}{F_1} \\ a = \frac{C_3 + G_3 b}{F_3} \end{cases}$$

yielding

$$b^{CM} = \frac{G_1 C_3 + C_1 F_3}{F_1 F_3 - G_1 G_3} \tag{18}$$

$$a^{CM} = \frac{G_3 C_1 + C_3 F_1}{F_1 F_3 - G_1 G_3}. \tag{19}$$

5 Membership game

We now solve the first stage of the game where countries decide on their membership status, taking into account the equilibrium adaptation and emission decisions of countries in each group. We adopt the noncooperative point of view, where successful agreements must be self-enforcing, and we apply the stability concept introduced in d'Aspremont et al. (1983), such that signatories have no incentive to leave the agreement, while nonsignatories have no incentive to join the agreement. This translates into the internal and external stability conditions based on the free-riding incentive generated by a unilateral deviation.

The internal stability criterion requires that no participating country can improve its utility by unilaterally leaving the agreement (that is, by assuming that no other country changes its membership status). In the same way, the external stability criterion requires that no non-participating country can improve its utility by joining the agreement, assuming once again that the membership status of other countries remains unchanged. Therefore, an agreement involving n signatories is stable if

$$U_i^{S*}(n) \geqslant U_i^{NS*}(n-1) \text{ for } i = 1, ..., n \tag{20}$$

$$U_j^{NS*}(n) \geqslant U_j^{S*}(n+1) \quad \text{for } j = 1, ..., m, \tag{21}$$

where $U_i^{S*}(n)$ and $U_j^{NS*}(n)$ are, respectively, the equilibrium utility of the signatory and non-signatory countries, that is, the utilities corresponding to the solution of the adaptation game when the number of signatory countries is n.

The stability conditions (20)–(21) can be checked around the root of the stability function

$$\psi(n) \equiv U^{S*}(n) - U^{NS*}(n-1), \tag{22}$$

and the agreement is stable for a discrete number $n^*$of participating countries iif $\psi(n^*) \geq 0$ and $\psi(n^* + 1) \leq 0$.[10]

Note that, even if the equilibrium solution of the adaptation game and the stability function can be expressed analytically, it is not possible to compute the root of the stability function in closed form. It is however straithforward to obtain this root numerically for any set of parameters.

We investigate our research questions by performing an extensive numerical exploration of the set of feasible model parameter values. Results and illustrative examples are presented in the next section.

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[10] If the stability function is non-negative over the interval $[1, N]$, then the solution of the membership game is full participation. If the stability function is always negative, or is increasing at the root(s), then there exists no stable agreement and the solution of the membership game is $n^* = 0$.

6 Results

In this section we report and discuss the results of our investigation that focuses on four main questions: the consequences of increasingly ambitious pledges, the impact of adaptation, the convenience of signatories coordinating their adaptation level, and the design of an ideal agreement. The analysis is developed at the stable size of the agreement, and results rely on an extensive numerical exploration of model parameter values, in the space of reasonable values, that is, where equilibrium emissions and vulnerability in both groupes of countries are positive for $n = 1, ...N$, and where optimal adaptation levels are positive and high enough to make a difference in the utility of the countries.

6.1 Ambition

We first investigate the impact of the ambition of the pledge[11] on participation to the agreement, adaptation levels (when this is an option), emissions, and welfare. This investigation is carried out to understand the consequences of one of the main points in the Paris Agreement, stating that countries must increase their effort in reducing GHGs emissions (Articles 4 and 6).

Since all three models yield qualitatively similar results, illustrative examples are provided for the AM-model only. Parameter values for the base case are reported in Table 1, where the reference point r is the Nash solution where all countries choose their emission levels independently (no adaptation, no agreement).

Table 1: Base-case parameter values, AM-model.

N	d_1	d_2	γ	r	c
100	0.0023	0.5	0.3	0.99008	1

Increasing the ambition of the pledge results in a reduction of the number of signatory countries (Figure 1); since the utility of signatory countries is more sensitive than that of non-signatories to the value of α, an increase in ambition shifts the stability function and results in a lower participation. Figure 1 also shows that the ambition of the pledge has a negative impact from an environmental point of view, as the decrease in participation to the IEA results in a higher global level of emissions.

It is interesting to observe that individual emissions by both types of countries are decreasing with α – at a much higher rate for signatory countries. However, because of the reduction in participation, while the aggregate emissions of signatory countries decrease, the aggregate emissions of non-signatory countries increase, leading to a net increase in total emissions (Figure 2). Nevertheless, for any level of positive participation to the agreement, total emissions are still lower than the Nash solution, making the agreement effective from an environmental point of view.

While one could expect that more ambitious pledges to reduce emissions would decrease the need for adaptive investment, the reverse is observed in equilibrium: adaptation investments by both types of players increase with the ambition of the pledge (Figure 3). This is due to the increase in total emissions resulting from more ambitious pledges, thus increasing countries' vulnerability. Note that, in equilibrium, non-signatory countries always invest slightly (for this illustrative example, less than 0.0002%) more than signatory countries in adaptation, and this difference is decreasing with ambition.

Increasing the ambition level also causes a decrease in the individual utility in both groups of countries (since the agreement is stable, the individual utilities of signatory and non-signatory countries are very close). Figure 4 shows how the individual welfare (revenues from production minus damage and adaptation costs) of countries varies with the value of α. Note that the difference between the welfare and the utility of signatory countries is the self-image component, which increases with ambition (in

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[11] For a given regeference point, increasing the ambition of the pledge results in more stringent (lower) emission targets.

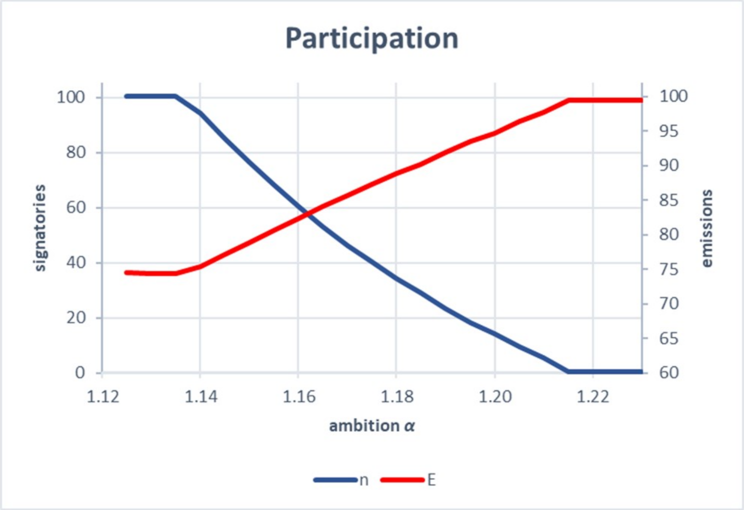

Figure 1: Impact of the ambition of the pledge (parameter α) on the number of signatory countries and on the total emissions. Parameter values are reported in Table 1.

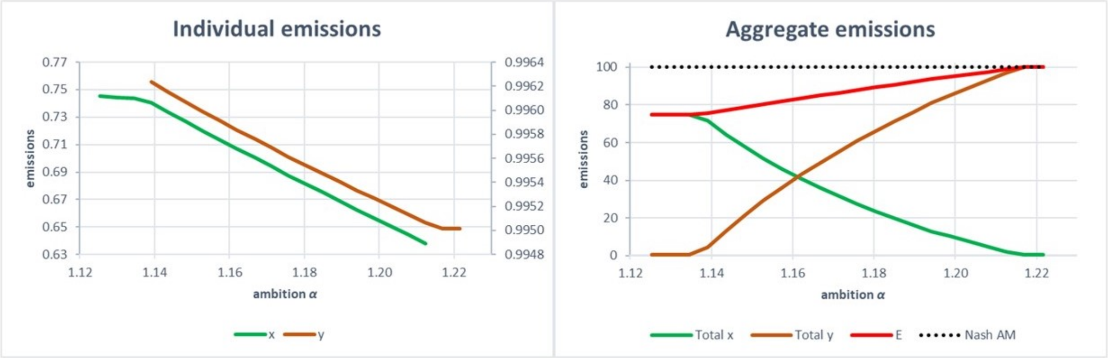

Figure 2: Impact of ambition on individual and aggregate emissions of countries. Parameter values are reported in Table 1.

this specific case, self-image is relatively important, accounting for between 10% to 25% of the utility of the signatory countries).

However, even though utility and welfare are decreasing with ambition, we observe that for any level of positive participation to the agreement, the overall welfare is greater than in the Nash solution, making the agreement also effective from an economic point of view.

The overall picture from this investigation is that increasing ambition levels reduces participation to the IEA, so that the collective effort in reducing emissions decreases; even if countries respond with increasing levels of adaptation, this is not enough in terms of overall performance, as countries experience a decreasing utility. This suggests that wide and shallow agreements are better than narrow and ambitious ones, and that participation to an IEA is fundamental in the response to climate change.

The results reported in this section are robust to changes in model parameter values; such changes shrink and/or shift the interval of values for the ambition parameter α that supports any participation to the agreement. For instance, an increase in the damage parameter d_2 shifts the interval to the left, so that, for a given level of ambition the size of stable agreement is lower with increasing d_2 and therefore the agreement breaks down at a smaller ambition level. On the other hand, an increase in the awareness and concern for the climate change problem (parameter γ) shifts the interval to the

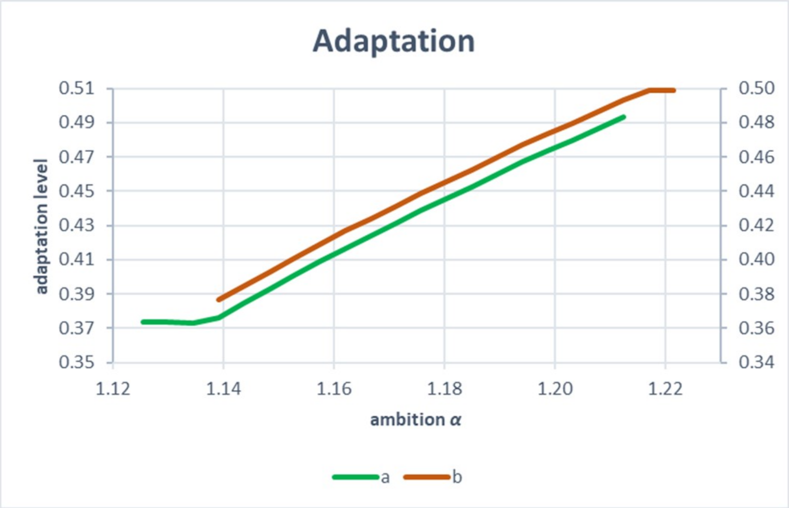

Figure 3: Impact of the ambition of the pledge (parameter α) on the adaptation levels of signatory (left axis) and non-signatory (right axis) countries. Parameter values are reported in Table 1.

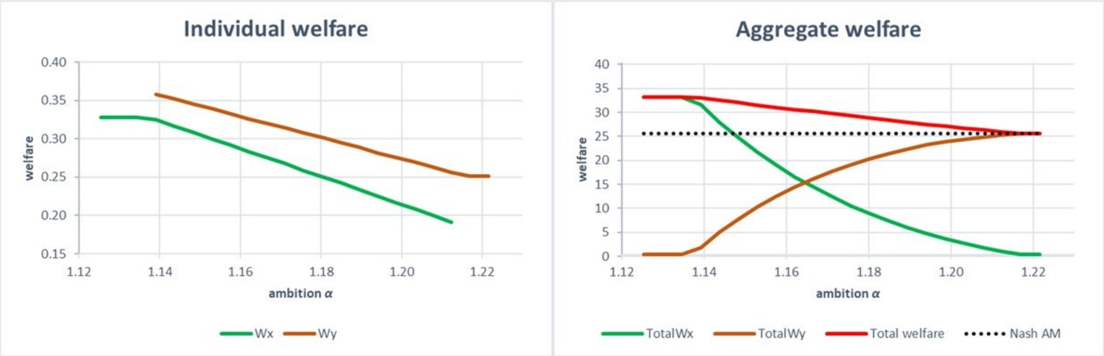

Figure 4: Impact of the ambition of the pledge (parameter α) on the aggregate welfare in each group and on the total welfare. Parameter values are reported in Table 1.

right, so that for a given level of ambition we observe a greater participation to the agreement with increasing γ and the agreement breaks down at a higher ambition level.

6.2 Adaptation

Our second investigation addresses the convenience and consequences of investing in prior adaptive solutions as an additional response to climate change. This is done by comparing the BM-model (no adaptation) with the AM and CM models, namely by comparing their outcomes in terms of participation, total emissions, and welfare.

A first crucial observation is that, for both the AM and CM models, the availability of adaptive measures never increases participation to the IEA with respect to the BM model. This result differs from what is reported in the literature where participants to an IEA agree to coordinate their mitigation efforts. Since the comparisons of the BM model against the AM and CM models produce qualitatively similar results, we use the AM-model and the parameters in Table 1 to illustrate our findings.

We start by discussing the instances where participation to the IEA is smaller when adaptation becomes available.

Figure 5 shows how participation to the IEA decreases with respect to the benchmark case for all values of the ambition parameter in the range yielding partial participation, resulting in an increase in total emissions.

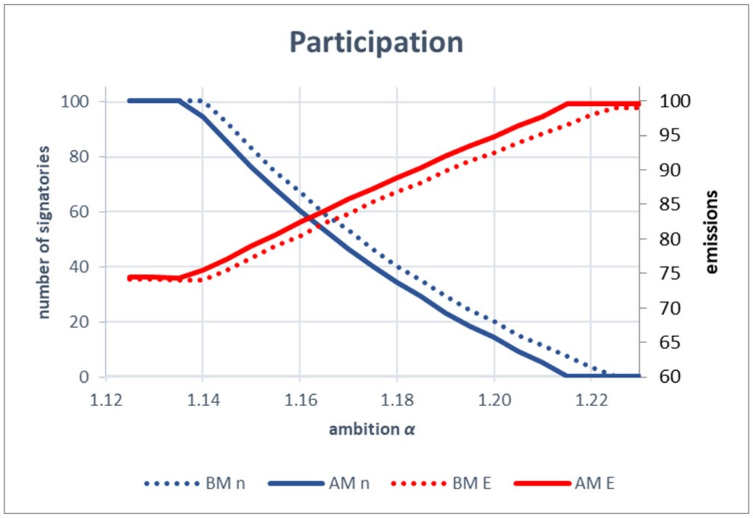

Figure 5: Comparison of the participation level and total pollution between the BM-model (no adaptation) and the AM-model (prior adaptation) over various values of the ambition parameter α. Other parameter values are reported in Table 1.

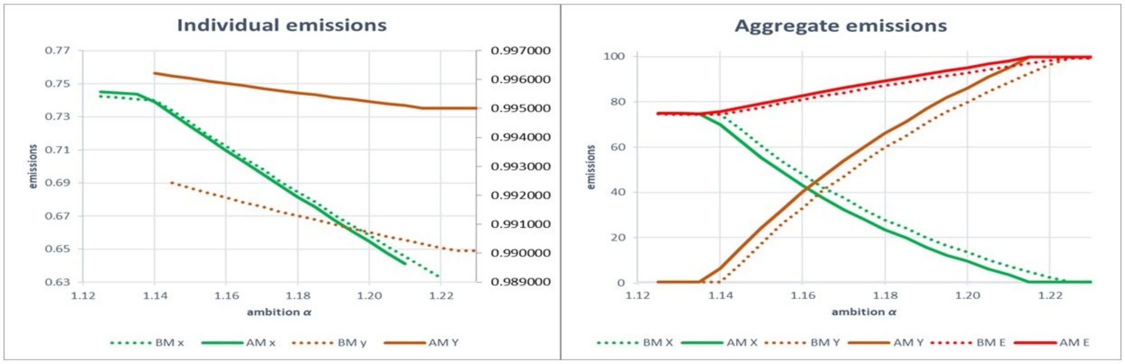

Figure 6: Comparison of the individual and aggregate emissions between the BM-model (no adaptation) and the AM-model (prior adaptation) over various values of the ambition parameter α. Other parameter values are reported in Table 1.

At both the individual and the aggregate levels, signatory countries emit less when they use adaptive investments, while non-signatory countries emit more. The overall result is a modest increase in total emissions, due to a combination of the increase in the individual emissions of non-signatory countries and in their number.

Figure 7 shows that the benefits of adaptation in reducing vulnerability and the damage cost far outweight its detriment in decreasing participation and increasing total emissions, in both groups of countries. Individual welfare of signatory and non-signatory countries increase, giving rise to a significant increase in the overall welfare. Note that the difference in welfare between the benchmark (without adaptation) and the AM and CM models at equilibrium increases as the participation to the agreement decreases.

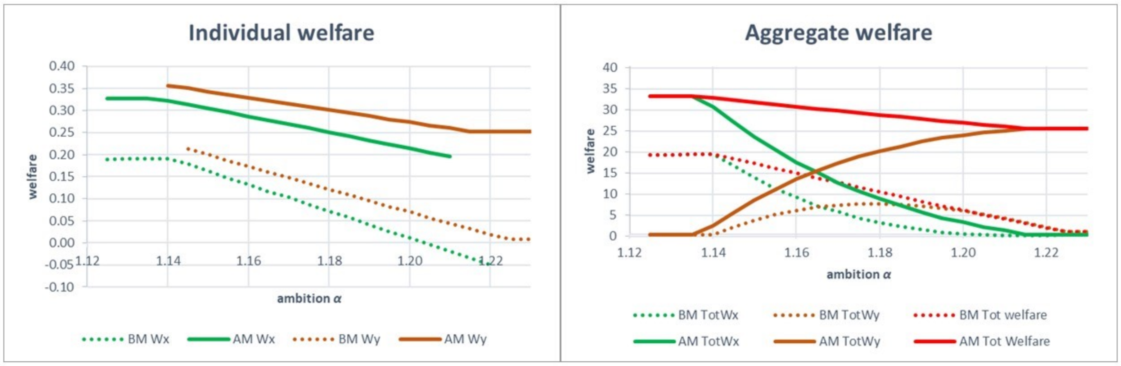

Figure 7: Comparison of the individual and aggregate welfare between the BM-model (no adaptation) and the AM-model (prior adaptation) over various values of the ambition parameter α. Other parameter values are reported in Table 1.

The above results are robust accross changes in model parameter values. Since, in equilibrium, non-signatory countries benefit more than signatories from the availability of adaptive measures, the stability function (Equation (22)) shifts downwards when adaptation becomes available (Figure 8), thus moving the root to the left.

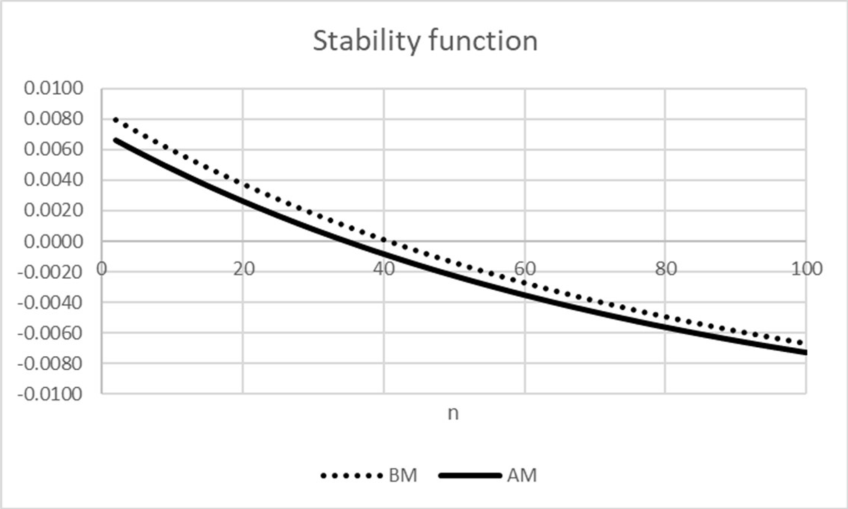

Figure 8: Stability function $\psi(n)$ for the AM and the BM models, at $\alpha = 1.18$. Other parameter values are reported in Table 1.

For some values of the model parameters, it may happen that the shift in the stability function is too small to change the integer stable size n^*. This happens when the equilibrium adaptation levels by both groups of countries are very low and do not impact their utility significantly (e.g. when the cost c of adaptation is high). In these cases, the impact of adaptation on emissions and welfare are still in the same direction, albeit very small, and we can conclude that instances where adaptation would not impact the size of the agreement are those where the benefits of using adaptation are not significant.

One interesting aspect that should be considered when adaptation is used in the context of an IEA is that adaptation modifies the level of ambition needed to reach a given participation target as, for example, the minimum participation clause in the Paris Agreement (Article 21). Table 2 compares the outcomes of the BM and the AM models when the emission target is adjusted in order to obtain a participation of 55%, using the base-case parameters provided in Table 1.

Table 2: Comparison of the outcomes from the BM-model (no adaptation) and the AM-model (prior adaptation) for a 55% level of participation. Parameter values are reported in Table 1.

			Emissions			Welfare	
	α	Target	S	NS	Average	S	NS
BM	1.168	0.8477	0.7008	0.9917	0.8317	0.1075	0.1522
AM	1.1635	0.8509	0.7046	0.9958	0.8357	0.2808	0.3244
% inc.		0.39%	0.55%	0.42%	0.48%	61.73%	53.08%

We find that, for a given participation target, the availability of adaptative measures can lead to less ambitious targets, and that this is welfare enhancing for both signatory and non-signatory countries.

To conclude about the convenience of using adaptive measures as a response to climate change, our investigation indicates that investments in adaptation are beneficial in general, even if there may be a loss in participation to the agreement, and even if they result in an increase of the overall emissions.

6.3 Coordinating adaptation

We finally assess the issue of signatory countries coordinating their adaptation decisions. This analysis is motivated by the numerous mentions of such cooperation in the Paris Agreement, such as in Articles 6, 7 and 8.

A first observation, stemming from an extensive exploration of model parameter values, is that coordination of adaptation decisions among signatory countries (CM-model) does not change the level of participation to the IEA with respect to the AM- model, where countries decide on their adaptation investments individualistically.

As expected, at a given participation level, cooperation in adaptation is beneficial for signatory countries, and it results in a decrease in their collective adaptation level. Moreover, because the adaptation reaction functions between the two groups are upward sloping, cooperation also leads to a reduction in the level of adaptation of non-signatory countries (albeit to a lesser extent). As a consequence, individual and aggregate emissions are smaller, which results in a higher individual and global welfare.

To conclude, it is important to note that, since participation is not affected by coordinating adaptation, differences in emissions and welfare between the AM and the CM models are modest. They are more pronounced when the level of participation to the agreement is high, as this is when cooperation is most effective.

6.4 Design

On the basis of the previous results, it seems that the ideal agreement, in a context where signatories are not required to coordinate their emissions, would provide for adaptation, propose a modest common target in order to reach full participation, and suggest that signatory countries coordinate their adaptive investments. One interesting issue is to find the level of ambition that maximizes countries' welfare and how it is affected by the presence of adaptation.

We already obtained in Section 6.1 that welfare is maximized at an ambition level ensuring full participation. The ideal ambition level is then the one maximizing the welfare of signatory countries among the ones ensuring full participation.[12]

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[12] Recall that the range of ambition levels ensuring full participation cannot be obtained in closed form.

In the BM-model, we can determine the ambition level maximizing the welfare of signatory countries under full participation (see Appendix A1.4):

$$\alpha^* = \frac{r\gamma\left(2d_2+1\right)+\left(N-1\right)\left(d_1+2d_2\right)}{\gamma\left(1-d_1\right)\left(N+1\right)} > 0. \tag{23}$$

Equation (23) gives the value $\alpha^*$of the ambition parameter that maximizes the total welfare at $n = N$, given the equilibrium emission level, without accounting for the stability condition (20).

If Condition (20) is satisfied at (α^*, N), then the optimal level of ambition in the BM-model is α^*. Otherwise, the optimal level of ambition is $\widehat{\alpha} < a^*$, where $\widehat{\alpha}$ is defined as the largest α ensuring full participation.

It is interesting to note that when Condition (20) is satisfied at (α^*, N), the optimal level of ambition is even smaller than $\widehat{\alpha}$: in that case, lowering the ambition does not change participation, but is still welfare-enhancing. For this to happen, the value of parameter γ should be relatively high (see Appendix A1.4).

In the AM and CM models, it is no longer possible to analytically obtain information about the optimal level of ambition. Extensive numerical experimentations show qualitatively similar results in these cases, whith the additional observations that

- For a given set of parameter values, the optimal value of the ambition parameter is slightly smaller in the AM-model than in the CM-model, and significatively smaller in the CM-model than in the BM-model.
- The optimal value of the ambition parameter is increasing with the cost of adaptation c.

Moreover, these results can be observed whether or not the optimal level is at α^* or at $\widehat{\alpha}$, and it can happen that the best level in the BM-model is at $\widehat{\alpha}$ while it is at α^* in the AM or CM models, and conversely.

These results allow us to conclude that adaptation allows to design efficient aggreements with less ambitious targets than in the benchmark model: when adaptation is available, countries will maximize their welfare at a less stringent target, because adaptation is used to compensate the damage from higher emissions.

7 Conclusions

As extreme weather events are occuring more frequently and are becoming more intense, countries must ramp up their efforts toward both mitigation and adaptation. This paper has examined how investments in adaptive measures influence participation and effectiveness of international environmental agreements. Specifically, regarding adaptation, we considered long-term, somewhat irreversible investments requiring extensive planning, so that decisions in adaptive measures are made before deciding on emission levels. In terms of IEAs, we examined an agreement which calls signatory countries to publicly commit to a common emissions target, that they can reach in their most convenient way, and against which they will be assessed, leading to the inclusion of a “self-image” portion in their utility.

The analysis has been developed around three main questions: the consequences of inceasing levels of ambition in chosen emission targets, the impact of countries investing in adaptation measures and the consequences of coordinating adaptation efforts among signatory countries.

Our results show that setting more stringent emission targets leads to fewer countries participating in the agreement, negatively impacting all individual nations. This reinforces the critical importance of wide participation in an international environmental agreement to effectively combat climate change. On the other hand, we find that while adaptation generally reduces participation to an IEA and enables countries to increase global emissions, the overall benefits from adaptation measures are positive.

Finally, we observe that regulating adaptation efforts within an IEA focused on emission targets does not impact countries' participation levels. However, coordinating adaptation through the agreement can further enhance both signatory and non-signatory countries' welfare.

Our results significantly differ from prior findings in the literature on agreements-emissions-adaptation. The general conclusion from that body of work is that adaptation efforts improve participation in international environmental agreements. The reason for this discrepancy lies in the difference in the terms of the modeled agreements. In the "classical" literature, the agreement requires signatories to coordinate their actions for the coalition's collective good. In contrast, in the agreement modeled in our paper, countries only commit to an emissions target that they can meet through their own means. This mirrors the bottom-up approach of the Paris Agreement, which has been viewed as fundamental to achieving its nearly universal participation.

This divergence highlights the importance of the specific modeling framework adopted and broadens our understanding of how various agreement models can impact efforts to address climate-related challenges.

A1 Appendix

A1.1 Damage function

Consider a reference case where all countries are symmetric and emitting at the same level x, so that $E = Nx$, and where adaptation is not available. The welfare of a representative country is then given by

$$W(x) = \left(1 - \frac{x}{2}\right) x - d_1 x - d_2 x^2.$$

Maximizing this function with respect to the emission level $x \geq 0$ yields the first-best solution. The maximum of this function is attained at

$$x^* = \frac{1 - d_1}{2d_2 + 1}$$

and the maximum welfare is equal to

$$W^* = \begin{cases} \frac{1}{2}\frac{(1-d_1)^2}{2d_2+1} \text{ if } x^* \geq 0 \\ 0 \text{ otherwise.} \end{cases}$$

If $d_1 \geq 1$, revenues from production cannot exceed damages, and the best solution for all countries is not to produce.

A1.2 Vulnerability

It is easy to check from the reaction functions of both types of countries (Equations 12, 13, 17 and their corresponding coefficient values) that the equilibrium adaptation in all models is decreasing in the parameter c. If the cost of adaptation were too low, it could happen that vulnerability becomes positive, and the damage function would no longer make sense. Since adaptation is decreasing in n in both groups of countries, an approximate bound for c can be found by examining the solution at $n = N$ in the AM-model.

In that case, the vulnerability is computed using

$$\widetilde{a} = a^{AM}(0; N) = \frac{C_2}{F_2}$$
$$\widetilde{x} = x(\widetilde{a}, 0; N) = S_1 + S_5 \widetilde{a},$$

so that

$$\widetilde{x}-\widetilde{a}=S_1+\left(S_5-1\right)\frac{C_2}{F_2}.$$

Positive vulnerability then reduces to the condition

$$F_2>\frac{C_2\left(1-S_5\right)}{S_1}=C_2\frac{N+\delta+N\delta}{N-d_1+T\delta},$$

or, equivalently,

$$c>C_2\frac{N\delta_0+\delta}{N-d_1+T\delta}+F_0$$

with

$$\begin{aligned}
F_0 =&-2N^6d_2\left(N\delta_0+\delta\right)\frac{2d_2N_1+N\left(N\delta_0+\delta\right)}{H^2}+4d_2^2N^2\frac{\delta_0\left(H-2Nd_2\right)-N\delta^2N_1}{H^2\left(N+\delta\right)}\\
C_2 =&N^2\frac{2N\left(d_1+d_2\right)+\delta d_1\left(2N+1\right)}{H}\\
&+2NN_1d_2\left(\frac{2d_2+d_1\left(N+2\delta\right)}{H}+N^2\frac{\left(-2d_2+\delta^2\right)\left(N-d_1\right)}{H^2\left(N+\delta\right)}\right)\\
&+2N^3T\delta d_2\left(\frac{N_1\left(2d_2N_1+N^2\delta_0\right)}{H^2\left(N+\delta\right)}+\frac{N+2\left(d_2+N\delta\right)}{H^2}\right)\\
\delta_0 =&\delta+1\\
N_1 =&N-1\\
H =&\left(N^2\left(N+\delta\left(N+1\right)+2d_2\right)\right)
\end{aligned}$$

A1.3 Impact of participation in the BM-model

In the BM-model at equilibrium, an increase in the number of signatories allows each individual signatory and non-signatory to increase their respective emissions, but reduces the amount of total emissions. Using Equations (7)–(8), we obtain

$$\begin{aligned}
\frac{dy(n)}{dn} =&2N\delta d_2\left(N+\delta\right)\frac{\left(N+1\right)\left(N-d_1\right)+T\left(N+2d_2\right)}{\left(N^2\left(N+\delta\left(n+1\right)\right)+2d_2\left(\delta m+N^2\right)\right)^2}>0\\
\frac{dx(n)}{dn} =&N^2\delta\left(2d_2+N\delta\right)\frac{\left(N+1\right)\left(N-d_1\right)+T\left(N+2d_2\right)}{\left(N^2\delta+2N^2d_2+N^3+2N\delta d_2-2n\delta d_2+N^2n\delta\right)^2}>0\\
\frac{dE(n)}{dn} =&-N^3\delta\left(N+\delta\right)\frac{\left(N+1\right)\left(N-d_1\right)+T\left(N+2d_2\right)}{\left(N^2\left(N+\delta\left(n+1\right)\right)+2d_2\left(\delta m+N^2\right)\right)^2}<0.
\end{aligned}$$

A1.4 Optimal ambition

In the BM model, we find the ambition level maximizing the signatory countries' welfare, that is

$$\begin{aligned}
W_i^S =&\left(1-\frac{x_i}{2}\right)x_i-d_1x_i-d_2x_i^2\\
=&x_i\left(\left(1-d_1\right)-x_i\left(d_2+\frac{1}{2}\right)\right).
\end{aligned}$$

Using $\delta\equiv\alpha\gamma$ and $T\equiv\frac{r}{\alpha}$, the equilibrium emission level at $n=N$ is given by Equation (8):

$$x_i=\frac{\left(N-d_1+r\gamma\right)}{\left(N+2d_2+\alpha\gamma\left(N+1\right)\right)},$$

and the impact of α on the welfare of signatory countries at N is then given by

$$\frac{dW_i^S(\alpha)}{d\alpha} = \gamma\left(N+1\right)\frac{N-d_1+r\gamma}{\left(N+2d_2+\alpha\gamma\left(N+1\right)\right)^3}M$$

where

$$M = r\gamma\left(2d_2+1\right)+\left(N-1\right)\left(d_1+2d_2\right)-\alpha\gamma\left(1-d_1\right)\left(N+1\right).$$

Therefore, the welfare of signatory countries is increasing in α for $a < a^*$ and decreasing in α for $a > a^*$, where

$$\alpha^* = \frac{r\gamma\left(2d_2+1\right)+\left(N-1\right)\left(d_1+2d_2\right)}{\gamma\left(1-d_1\right)\left(N+1\right)} > 0.$$

We conclude that α^* maximizes the welfare of signatory countries when $n = N$ at the equilibrium emission level, provided the stability condition (20) is satisfied at (α^*, N). If however Condition (20) is not satisfied at (α^*, N), then the optimal ambition level is $\widehat{\alpha}$, defined as the largest ambition level satisfying the stability condition at N, since the welfare of signatory countries at $n = N$ is increasing in α for $\alpha < \alpha^*$.

It is not possible to find an analytical characterization of the instances where the stability condition (20) is satisfied at (α^*, N). However, we can approximate the stability condition by comparing the utility of the signatory and non-signatory countries when $m \to 0$. The difference in utility is then

$$\Delta = \lim_{m\to 0}\left(1-\frac{x_i}{2}\right)x_i+\delta\frac{E}{N}\left(T-x_i\right)-\left(1-\frac{y_j}{2}\right)y_j$$

where the equilibrium emission levels are given by (7)–(8), yielding

$$\begin{aligned}\Delta =& \frac{\left(N-d_1+T\delta\right)\left(N+\delta\left(N+2\right)+d_1\left(\delta+1\right)+4d_2+T\delta\left(N+2d_2+N\delta-1\right)\right)}{2\left(N+\delta+2d_2+N\delta\right)^2}\\ &-\frac{\left(\delta\left(N\left(N+1\right)-2Td_2\right)-d_1\left(N+\delta+N\delta\right)+N^2\right)\left(\left(N+d_1\right)\left(N+\delta+N\delta\right)+2d_2\left(2N+T\delta\right)\right)}{2N^2\left(N+\delta+2d_2+N\delta\right)^2}\end{aligned}$$

Without loss of generality, we set $r = 1$ and obtain Δ as a function of the ambition parameter α:

$$\Delta = \frac{1}{2}\delta\frac{L}{\alpha N^2\left(N+\delta+2d_2+N\delta\right)^2}$$

where

$$\begin{aligned}L =& \alpha^2\gamma\left(N+1\right)^2\left(-N+d_1\right)\left(N+d_1\right)\\ &+\alpha\begin{pmatrix}-4d_2\left(N+1\right)\left(N^2-d_1\left(N+\gamma\right)\right)\\ +Nd_1\left(d_1\left(N+2\right)-N\left(\gamma\left(N-1\right)+2\right)\right)\\ +N^2\left(\gamma\left(N\left(N+1\right)+2\right)+N\left(\gamma^2-N\right)\right)\end{pmatrix}\\ &+\left(N+2d_2\right)\left(-N\gamma+2Nd_1+4Nd_2+2\gamma d_2+N^2\gamma-N^2d_1+N^3\right).\end{aligned}$$

Evaluating Δ at α^* yields

$$\Delta = \frac{1}{2}K\delta\frac{\left(N+\gamma-d_1\right)^2}{N^2\alpha\gamma\left(1-d_1\right)^2\left(N+1\right)\left(N+\delta+2d_2+N\delta\right)^2}$$

with

$$\begin{aligned}K =& \gamma N^3\left(2d_2+1\right)\left(1-d_1\right)\\ &-\left(N-1\right)\left(d_1+2d_2\right)\left(\left(2N+1\right)\left(d_1+2d_2\right)+N^2\left(2d_2+1\right)\right).\end{aligned} \tag{A1}$$

Note that the first term in Equation (A1) is positive, while the second is negative, for any feasible set of parameter values. Condition (20) is satisfied at (α^*, N) when there is no incentive for signatory countries to leave the agreement, that is, when Δ is positive. For this to happen, the value of parameter γ should be relatively high.

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